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The origin of sedimentary basins: a status report from the task force of the International Lithosphere Program*

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Better insights into the mechanisms of basin formation have a direct bearing on the predictive power of forward models for basin fill. Models that link flexure, normal faulting and thrusting on a subbasin scale provide important constraints on the tectonic control of the sedimentary record, enabling a quantitative comparison with eustatic contributions to the basin architecture. Thus of special importance is the need to link processes with different spatial and temporal scales involved in the evolution of extensional and compressional basins by numerical modelling. A new generation of basin modelling concepts and techniques is one of the main objectives of the Task Force Origin of Sedimentary Basins of the International Lithosphere Program. The focus of this work is on the quantification of the effects of the thermomechanical structure of the lithosphere and its interplay with regional and local stress changes. Other important developments include the step towards three-dimensional modelling and the full integration of rapidly expanding fission track and other data sets to constrain vertical motions in basins. As natural laboratories for the interactive testing and development of new basin modelling techniques, a number of basins with high quality data from industry, government and academia have been selected on the basis of specific testable problems.

Keywords: basin modelling; sedimentary basins; lithospheric evolution

The origin of sedimentary basins is a key element of the geological evolution of the continental lithosphere. During the last decade substantial progress has been made in understanding the thermomechanical aspects of sedimentary basin formation and the isostatic response of the lithosphere to surface loads such as basins (Braun and Beaumont, 1989; LePichon and Chamot-Rooke, 1991). Most of this progress has been made not so much in the development of new modelling methodologies or insights into the rheological make-up of the lithosphere, but rather in the processing of substantial, new, high quality data sets (e.g. *Figure 1*) from many parts of the globe (Tankard and Balkwill, 1989; Pinet and Bois, 1990; Klemperer and Hobbs, 1991; Ziegler, 1992; Bois, 1993).

Virtually all modelling carried out so far has been in terms of lithospheric displacements, without a full examination of dynamic controls exerted by

lithospheric stresses. This is because stresses are very sensitive to adopted lithospheric rheologies and the rheologies chosen have been by convention unrealistically simple (Vilotte *et al.*, 1993). This is true of models for both extensional and compressional sedimentary basins (Beaumont and Tankard, 1987; Ziegler, 1992). For example, most models for extensional basin formation are keyed to an observed lithospheric strain due to an unknown and unspecified stress field rather than to the strain response of the lithosphere to a known and/or realistic stress state. However, changes in plate tectonic regimes and associated stress fields have been shown to be significant in controlling the subsidence record and stratigraphic architecture of extensional basins (Cloetingh *et al.*, 1989; Cloetingh and Kooi, 1992; Zoback *et al.*, 1993). Similarly, models of basins developed in compressional environments have been conventionally related to load-induced flexure profiles (displacement patterns), again not invoking the dynamic control of the compressional stresses intrinsic to this particular tectonic setting.

Another reason that the relationship between lithospheric stresses and displacements in tectonic modelling has not received full attention is that little has been known about the actual stress state in the lithosphere. This situation has now changed (*Figure 2*) as the result of the successful World Stress Map Project



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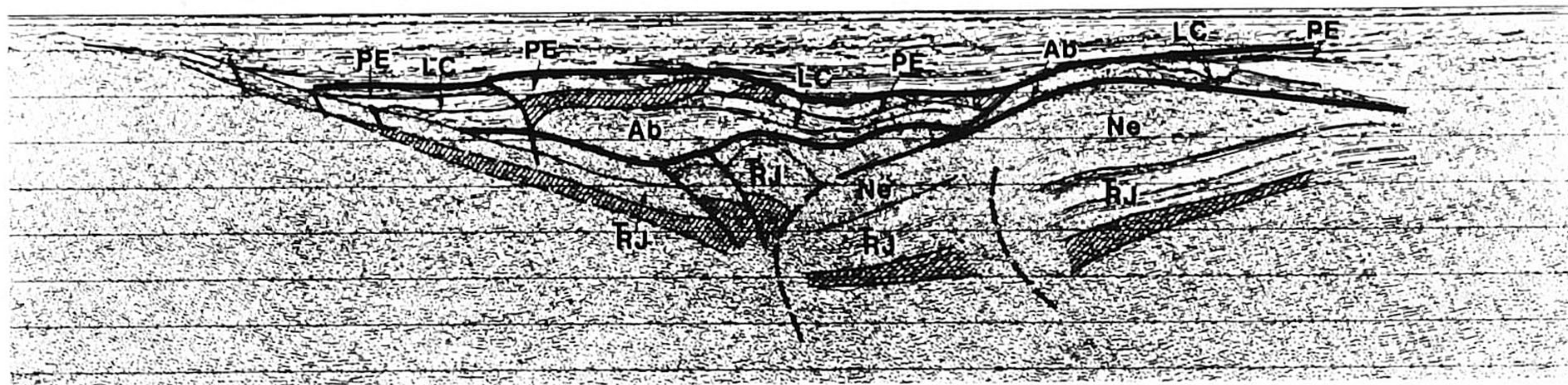


Figure 1 Geological interpretation of a migrated deep seismic section across the Bay of Biscay Basin (ECORS). PE = Palaeocene-Eocene; LC = Late Cretaceous; Ab = Albian; Ne = Neocomian; TRJ = Triassic-Jurassic. Hatched zones represent Triassic salt layers. After Bois *et al.* (1990)

carried out in the framework of the International Lithosphere Program (Zoback, 1992). Further, the application of structural techniques to establish the temporal evolution of palaeostress fields has begun in a number of sedimentary basins (Letouzey, 1986; 1990; Csontos *et al.*, 1991).

Not only has the dynamic element of lithospheric deformation been inadequately addressed, but present quantitative models of the origin of basins are incapable of solving problems related to subsequent structural developments that may be intrinsically coupled with the basin formation. For example, late-stage compression during the post-rift evolution of extensional basins can sometimes explain discrepancies between estimates of crustal thinning derived from structural analyses and subsidence data of rifted basins (Kooi and Cloetingh, 1989; Ziegler and Van Hoorn, 1989). Further progress in understanding the role of extensional faults in offshore areas such as the North Sea (Ziegler, 1990) requires detailed structural studies and modelling of exposed successions. Post-rift compression of extensional or transtensional sedimentary basins leads to complex near-surface deformation patterns. In such cases of structural inversion, inherited faults from the previous extensional phase (basement normal faults, frontal and lateral ramps, growth faults) may be reactivated and can strongly influence the deformation of the basin sediments. These mechanisms can explain, for example, various structures in foreland fold and thrust belts (Roure *et al.*, 1993; Sassi *et al.*, 1993) or telescoped wrench furrows.

To successfully develop dynamic models in which realistic constitutive relationships of the lithosphere are incorporated, it is obvious that more complicated rheologies, accounting for structural and transient material non-linearities, are necessary. Sufficient distributed computing power and adequate geological constraints are rapidly becoming available to the research community for these purposes.

To advance the study of basin dynamics, the Task Force Origin of Sedimentary Basins was formed at the initiative of the International Lithosphere Program. The Task Force consists of specialists in basin modelling as well as structural geologists, geophysicists and sedimentary geologists focusing on the interpretation of the basin record, from both academia and the petroleum industry. This group held a first workshop at the Institut Français du Pétrole in Paris

from 25 to 26 October 1990. Subsequent meetings and thematic field workshops were held at Matrahaza, Hungary in the Pannonian Basin (26 September–2 October 1991), in Sundvollen, Norway in the Oslo rift (18–23 August 1992) and in Benevento, Italy in the southern Apennines (25 September–1 October 1993).

This paper summarizes the discussions held during these meetings and outlines research strategies and goals of the Task Force. Individual papers describing research carried out in the framework of the Task Force have been published in two special volumes of *Tectonophysics* and *Sedimentary Geology* (Cloetingh *et al.*, 1993a, 1993b), with another volume with papers on the current state of modelling for basin extension and inversion in press (Cloetingh *et al.*, in press). We begin with a review of the three main research themes, followed by a discussion of the research strategy, in which integrated modelling using the basin inventory provided by natural laboratories in different tectonic settings plays a central part.

Themes for frontier research

Sedimentary basin evolution and the geometry of structures that are formed during the deformation of basins depend on many factors. The focus of the project is on interactive tectonic modelling with firm constraints from geological and geophysical data sets. The research programme aims at three closely interrelated major themes that are fundamental for our understanding of the dynamics of basins.

Appraisal of lithospheric deformation in basin dynamics in the context of the temporal and spatial evolution of lithospheric stresses

To understand this aspect of the origin and evolution of sedimentary basins we must understand what controls (i) where and why sedimentary basins develop, (ii) the rates and duration of subsidence and basin fill, (iii) uplift and erosion, (iv) structural style and changes of structural style with time, (v) salt tectonics and shale diapirism and (vi) heat transfer, fluid flow and rock–water interaction. To quantitatively address these issues, the interplay between lithospheric strength and stress is critically important as an overall constraint on lithospheric deformation.

In the context of the relationship between lithospheric stresses and basin development, we need to address a number of fundamental questions.

How are the dynamics of sedimentary basins tied to stresses in the lithosphere? In any model of basin evolution (Sleep, 1971; McKenzie, 1978; Wernicke and Burchfiel, 1982), heat plays a key part. The idea of lithospheric stretching — either homogeneous or inhomogeneous — implies that attenuation of the crust and mantle lithosphere is a major heat impulse into this dynamic system. After the termination of active rifting, basin evolution is controlled by the thermal contraction

of the lithosphere. The stratigraphic record suggests, however, that this simple process of basin evolution can be strongly modified by other forces such as a variation in intraplate stress.

The sources of stress in the lithosphere can be subdivided into several categories defined in the following. These stresses are by their nature of variable magnitude, ranging from several tens to as much as a few hundred MPa, comparable with the strength of the

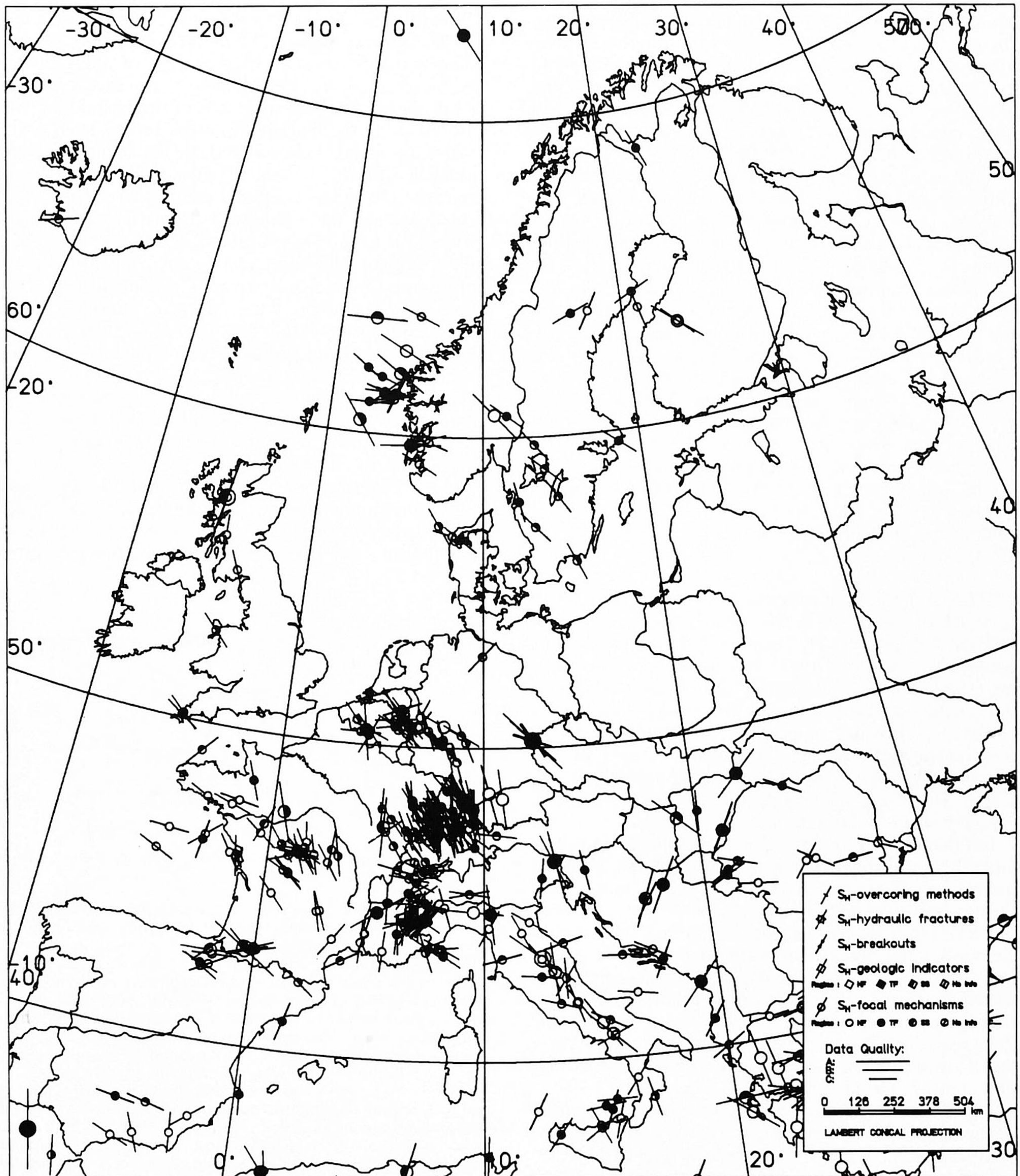


Figure 2 Western European part of the World Stress Map. After Mueller *et al.* (1992)

lithosphere. Stress concentration by geometrical focusing or local weakness zones can be a crucial factor in magnifying the stresses to a level comparable with lithospheric strength.

The question of whether lithospheric stresses remain relatively constant over time, as has been suggested for the Proterozoic Australian lithosphere (Lambeck, 1986), or vary episodically (Philip, 1987; Ziegler, 1988) is of fundamental interest for understanding the dynamics of basin formation. Studies of large-scale plate tectonic processes complemented by structural geological field studies on a much smaller scale have shown that, in some places, lithospheric stresses undergo important temporal changes in orientation and in magnitude. In particular, studies of the north-western European and Mediterranean stress field have revealed temporal changes on a characteristic time interval of 2–5 Ma (Philip, 1987).

Sources of stress in the lithosphere can be divided into stresses induced by plate tectonic forces and stresses generated by mechanisms operating on a regional scale as, for example, sediment loads within basins (see Zoback, 1992, for a review).

Stresses themselves and temporal changes in the stresses affecting the dynamic evolution of basins (Cloetingh and Kooi, 1992) are of prime importance. Forces operating on the lithosphere can change by, for example, changes in plate motion, conductive and convective cooling, sedimentation and deposition, sea-level changes, folding and thrusting, whereas changes in the stress state also occur as a result of stress relaxation over time. An important issue is how the interaction between internally and externally applied stresses affects the formation and evolution of sedimentary basins (Peper *et al.*, 1992; Zoback *et al.*, 1993).

What is the role of magmatism in intraplate basin formation and what deep-seated processes does it reflect? Within actively forming sedimentary basins, magmatism (Wilson, 1993) can occur in the form of intrusions (dykes, sills and plutons) and extrusions during discrete time intervals in the development of basins. It provides important information on the relationship between heat, magma pressure and the development of stresses in basins (Sundvoll *et al.*, 1992). However, this source of information is only rarely utilized in basin studies.

Regionally developed volcanic alignments and dyke and sill intrusions represent excellent palaeostress indicators. However, periods of active magmatism during basin formation are probably the combined effect of tectonic stresses and of heat flux. Magmatism can modify the stress distribution in a basin and lead to non-linear transient rheological heterogeneity in the lithosphere, affecting the lithospheric stress transmission on a regional scale. At the same time, the local rise of large volumes of hot magma into shallower levels of the lithosphere also alters the local rheology and creates thermal stresses.

The time of melting, the amount of heat, the density of the magma, the magma pressure (the buoyancy), the viscosity, the type of magmatism (extrusions in volcanoes, dykes, sills and plutonic intrusions) depend on the composition, volume and source depth of the

magma, as well on the thermomechanical conditions in the host lithosphere (Pedersen and Skogseid, 1989).

Of these physical parameters outside the magma body, the interplay of stresses and strength in the lithosphere is one of the main factors. Both shallow intrusions and extrusions are often characteristic of extensional basins, whereas in compressional regimes extrusives are rare and sill intrusions are, therefore, preferentially developed. Temporal and geometrical relations should provide valuable insights into the spatial distribution of stresses within basins. Observations in several basins (e.g. the Early Cretaceous magmatism at Svalbard and Franz Josephs Land and the volcanic rifted margin of mid-Norway; see Skogseid *et al.*, 1992a) show that extrusives often occur aligned to the central axis of the basin, with sills located along the margins. In other basins, such as the East Greenland Jamesonland Basin slightly off the initial line of North Atlantic rifting, sill emplacement concentrated in the deep and central part of the basin and decreased and shallowed towards basin margins (Figure 3). In the Oslo Graben (Sundvoll *et al.*, 1992), sills pre-date the main phase of volcanic activity represented by major extrusions of plateau lavas, the onset of which pre-dates normal faulting. These observations suggest that for the Oslo Graben a general decrease in magma pressures accompanied continued extension. In other basins, however (the Faeroe Islands), the occurrence of sills within thick sequences of plateau basalts is consistent with localized decreases in extension and the retention of high magma pressures during the rift–drift transition.

More examples of world-wide relationships with magmatism and stress in rifted basins, pull-apart basins and passive margins are needed. The use of phases of magmatism as stress indicators, although often

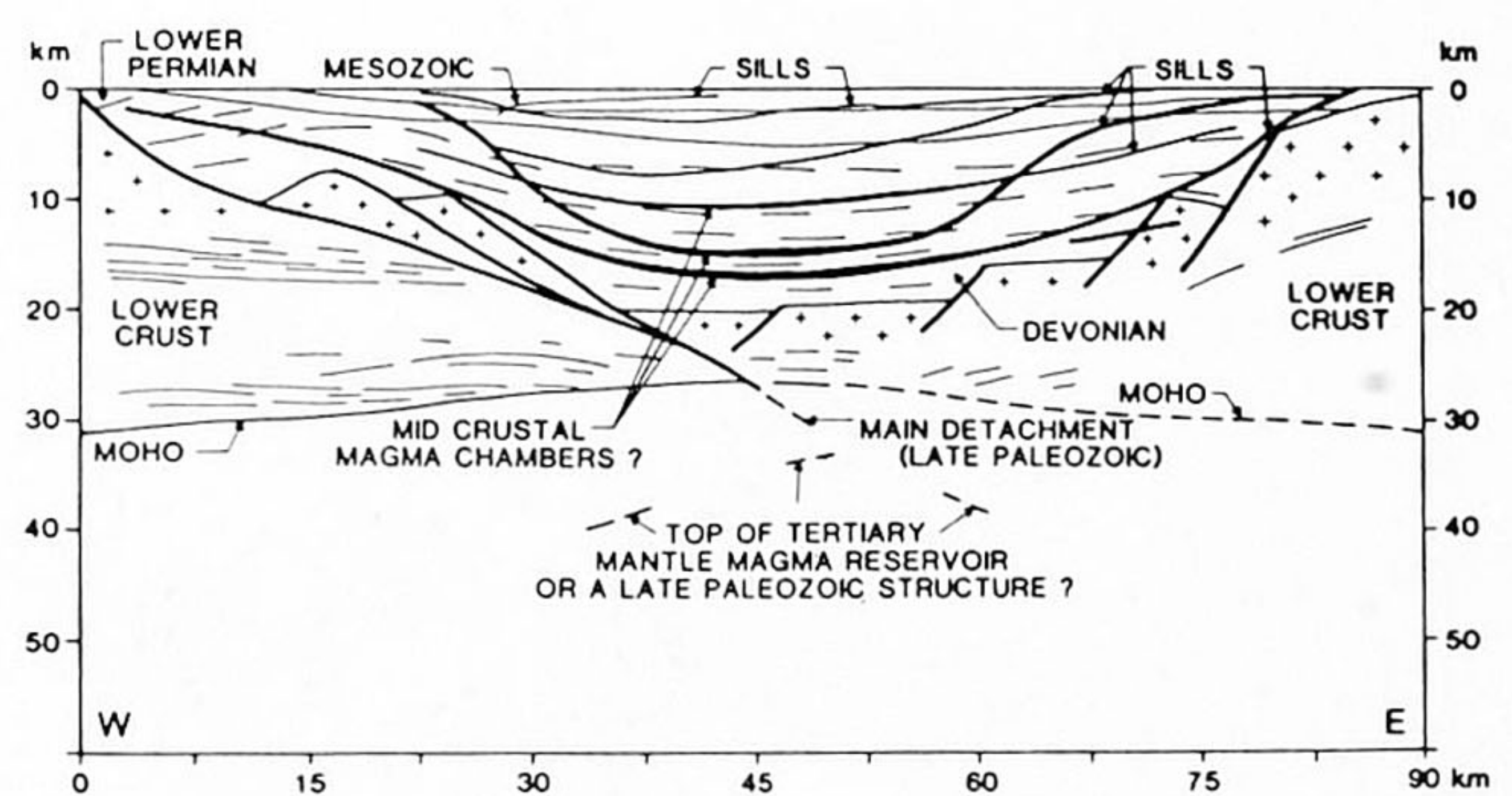


Figure 3 Simple shear model for the Late Palaeozoic to Mesozoic Jamesonland based on seismic data. The model illustrates some of the concepts and features discussed in the text. Pronounced and subhorizontal mid- and lower crustal seismic layering and a well defined reflection Moho are observed below the western half of the basin (lower plate), but is not present below the eastern half (collapsed upper plate), where only indications of a westward dipping crustal seismic layering locally are observed. Some subhorizontal to slightly dipping mantle reflectors (partly very strong) are present below the main basin trough. The main detachment is an eastward-dipping normal fault in outcrop. Early Triassic sills intruded the basin and probably sourced the formation of flood basalts at the surface. These were later removed by erosion after inversion and uplift. Note the time lag of a minimum of 200 My between the basin extension and break-up volcanism. From Larsen and Marcussen (1992)

overlooked, can give important additional information about the heat budget.

Volcanism and basin formation at rifted margins. Volumetrically, volcanism is normally subordinate to sedimentation as a basin-filling agent within intra-plate basins. This is also so along some nascent extensional plate boundaries such as the classical and mainly non-volcanic rifted continental margins. However, we know that the variation in processes and resulting range of basin and margin structures is indeed large. Some margins show thickening of the crust around the line of break-up, are very rich in volcanics and deform quite differently from continental rifts. In contrast, others are thin-crustal, volcanically more starved and deform similarly to some continental rifts (Figure 4). There is a growing understanding that this large variation in development may be related to very different mantle conditions during break-up. The temperature of the sublithospheric mantle seems to be of utmost importance and the role of plume-related hot-spots is a topic of much debate (White, 1992).

The recognition of volcanic rifted margins as a new class of rifted margins provides us with the opportunity of studying extensional processes and deformation of the lithosphere at different boundary conditions than those encountered in typical intra-plate rift systems. Because of the processes and strain rates operating in this extensional environment, synrift basin fill can sometimes be dominated by volcanics. In fact, no other exogene process can keep pace with the high strain rates in these basins, except perhaps evaporite formation.

Volcanic rifted margins are characterized by significant igneous-magmatic crustal accretion and substantial surface volcanism during continental break-up in which eruption occurs largely above sea level for some time after the initiation of continental drift. In cross-section a three-fold division can be made into a landward zone of plateau basalts, sills and dykes, a central zone of baselap-free, seaward-dipping and offlapping lava flow units (seaward-dipping reflector sequence; SDRS) and a seaward zone of 'normal'

oceanic crust generated at increasing water depth (Figure 4).

Deformation of the lithosphere, in the sense of emplacement of volcanics, takes place over very large areas during the formation of volcanic margins. Volcanic rifted margins commonly extend for more than 2000 km along-strike and associated continental flow basalts (CFBs) may reach as far inland as 1000 km from the line of continental break-up (Parana and Deccan traps). Surface expressions of lithospheric deformation are generally restricted to areas adjacent to the line of break-up. Thus the evidence for significant tectonic stretching and thinning of the crust and lithosphere (e.g. basement-involved normal faulting) is scarce and inconclusive, but could be masked by the CFBs and/or the feather edge of the SDRS. On the other hand, CFBs show marked faulting and downflexure along narrow, margin-parallel deformation zones relatively close to the line of break-up. These flexures seem to mark the transition from relatively non-deformed lithosphere into deformed and downflexed continental lithosphere below the onlapping feather edge of the SDRS. Clearly the effective elastic thickness and flexural rigidity of this downflexed continental lithosphere is much reduced. There is at present no confirmed model for this weakening of the lithosphere which seems to allow excessive strain rates, e.g. 5 km of subsidence in perhaps less than one million years (Larsen and Jacobsdottir, 1988).

The mid-Norway margin (1000 km long) (Skogseid and Eldholm, 1987; 1989) and the East Greenland margin (2000 km long) (Larsen and Jacobsdottir, 1988) provide excellent sites for the modelling of volcanic rifted margin evolution. The academic and commercial seismic database of the mid-Norway margin is large and of high quality, and more than 60 exploration wells have been drilled. The margin was subjected to long-lived extension with two distinct phases of rifting in Permo-Carboniferous, and Late Jurassic to Early Cretaceous times, followed by break-up in Early Eocene time. After break-up the area was affected by a compressive stress regime (Jensen *et al.*, 1992). Spatial

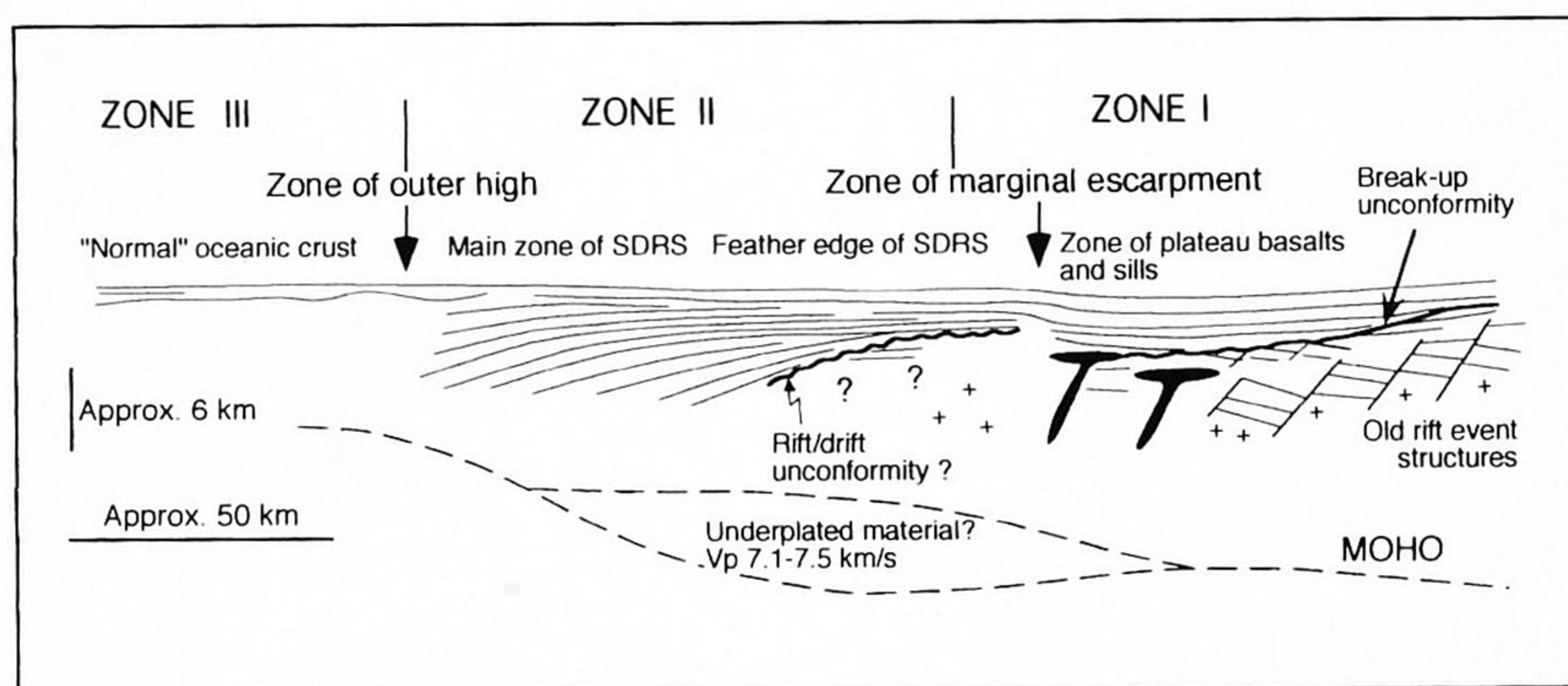


Figure 4 Idealized zonation of a volcanic rifted margin. If no significant pre-break-up basin is present, the inner zone (I) may simply develop as a basement arch with or without a continental flood basalt cover. Zone II is dominated by the excessive volcanic cover showing the characteristic baselap-free, offlapping and seaward-dipping reflector pattern originating from groups of mainly subaerial lava flows emplaced from the downdip direction and later downflexured into their present dip. Zone III is the transition zone into normal oceanic crust which formed at bathyal water depths and with a normal thickness of extrusives. Position of the Jamesonland Basin (Figure 3) would be in the middle of zone I. From Larsen and Marcussen (1992)

variations in sill intrusions observed in seismic lines east of the volcanic high, with sills intruding deeper to the east, offer the chance to study the role of lateral changes in the stress field on the basin formation process. Both folding and doming and landward uplift and seaward tilting are excellently expressed. The Vøring margin, the central segment of the mid-Norway margin, provides a structural, stratigraphic and magmatic record which allows the investigation of the spatial and temporal relationships between rifting and

magmatism associated with continental break-up, as well as the pattern of basin formation due to earlier tectonic episodes (Figure 5A). Particularly striking (Eldholm *et al.*, 1989) is the observed spatial correlation between shallow crustal faulting (Figure 5B), igneous activity (Figure 5C) and tectonic subsidence (Figure 5D), reflecting the coupling between lithospheric and crustal deformation. The basin record shows that the sublithospheric thermal conditions allowed melting to occur over almost the entire width

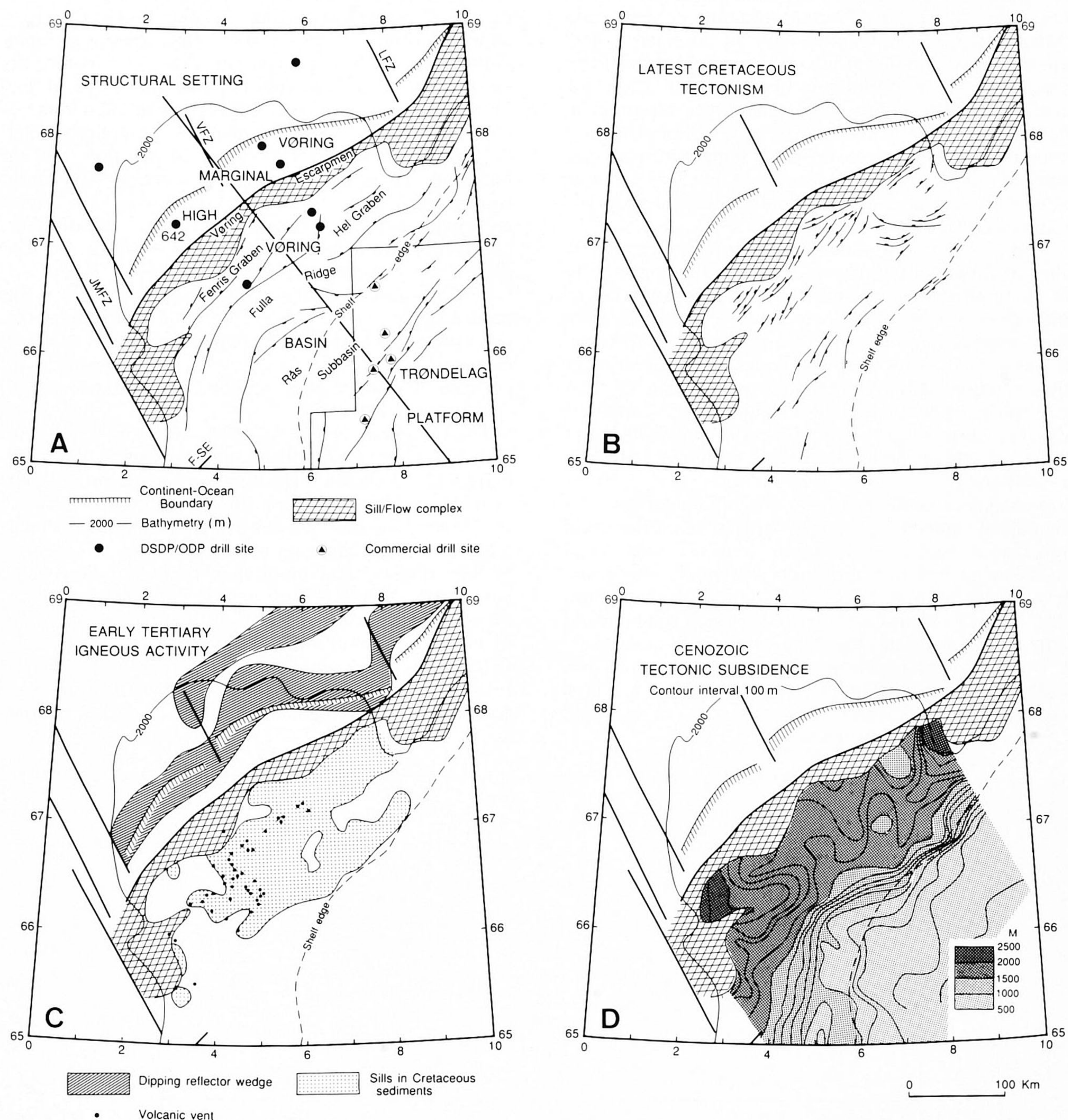


Figure 5 (A) Structural setting of the Vøring margin defined as the base Cretaceous level. Commercial exploration area with selected wells is marked in lower right corner. Location of profile given in Figure 6 is indicated. (B) Distribution of latest Cretaceous tectonism as defined by normal faulting. (C) Distribution of Early Tertiary igneous activity. (D) Cenozoic tectonic subsidence. Compiled from Skogseid and Eldholm (1987) and Skogseid *et al.* (1992a). F-SE = Faeroe-Shetland Escarpment; JMFZ = Jan Mayen Fracture Zone; VFZ = Vøring Fracture Zone; and LFZ = Lofoten Fracture Zone

of the rift (Figure 6), over an area more than 300 km wide, also taking the north-east Greenland margin into consideration (Skogseid *et al.*, 1992a; 1992b).

The East Greenland margin locally shows a long history of extensional (and compressive) deformation (Larsen and Marcussen, 1992). A recent ODP drilling leg has provided important additional data to constrain the history of volcanic rifted margin formation in the northern Atlantic. The East Greenland margin shows considerable variation along-strike in pre-break-up structure and also different break-up and post-break-up developments are present, providing multifold possibilities for modelling the process at various boundary conditions. In the south, Early Tertiary break-up took place in an essentially non-deformed (no sign of strong rifting) cratonic basement area (marginal part of the Canadian–Greenland Shield). In the north break-up was preceded by rifting and basin formation since the Devonian within the Caledonian fold belt. Pre-existing basins were intruded by sills (Figure 3) and partly overlain by volcanics.

A complex development characterizes the central East Greenland margin with a later Mid-Tertiary rift propagation from the Iceland hot-spot and into the Early Tertiary rifted continental margin. The younger oceanic lithosphere forming in response to northward rift propagation was tectonically decoupled from the older margin structures and shows extreme subsidence (5–7 km) due to sediment loading. The northern margin segment and the southern margin segment in particular show much more limited subsidence. The onshore regions in general show marked uplift of the order of 1–2 km (locally more). Differential vertical movements within the East Greenland margins thus

approaches 10 km in post-break-up time.

Differences in basin formation style between intra-plate rifts and non-volcanic rifted margins on one hand and volcanic rifted margins on the other could indicate different processes of lithosphere thinning operating in the two environments. It is therefore important to model the deformation of the lithosphere within the 'volcanic basin' environment.

Stress and flexure of the lithosphere under basins.

Numerical modelling studies have already shown the key part intraplate stresses play in shaping the stratigraphic record of sedimentary basins (Cloetingh *et al.*, 1985; Kooi and Cloetingh, 1992; Van Balen and Cloetingh, 1994). During the rifting stage, the process of necking in a tensional stress regime (Braun and Beaumont, 1989; Weissel and Karner, 1989) can lead to the rapid uplift of rift shoulders (Figure 7a). Changes in stress level in the post-basin formation stage induce rapid changes in subsidence and produce differential vertical motions (Figure 7b) and sequence boundaries strikingly similar to those generated by eustatic events (Figure 7c) within sedimentary basins. These stress-induced rapid vertical motions affect estimates of crustal extension derived from the post-rift subsidence history of rifted basins and are also of importance for diapirism and fluid flow (Figure 7d) within the basins (Van Balen and Cloetingh, 1993). Non-thermal components in the post-rift tectonic subsidence record of extensional basins might have a number of interesting consequences for the explanation of, for example, the occurrence of episodic dewatering and hydrofracturing events (Cartwright, 1994) and other anomalous events in groundwater flow (Ballentine *et al.*, 1991), diagenesis and cementation (Robinson *et al.*,

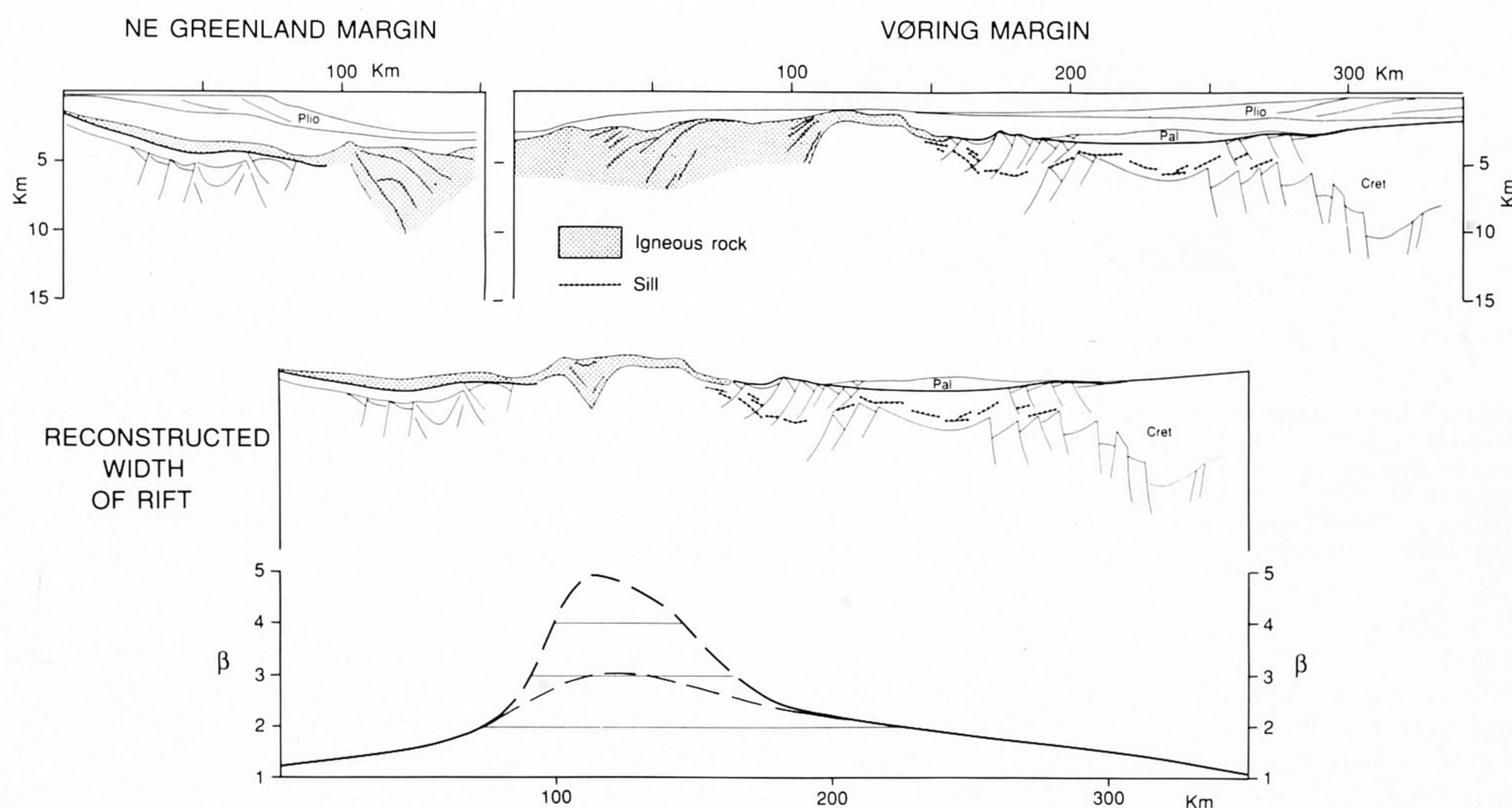


Figure 6 Top panels: interpretation of seismic profile BGR 88-14 on the north-east Greenland margin and the composed profile VB-185/C164 on the Vøring margin. Bottom panel: reconstruction of the Late Cretaceous–Eocene rift with associated tectonic subsidence derived β distribution. The igneous activity mirrors the β distribution and intrusions dominate the Mesozoic Vøring Basin. Extrusives appear to have dominated the north-east Greenland margin. From Skogseid *et al.* (1992a)

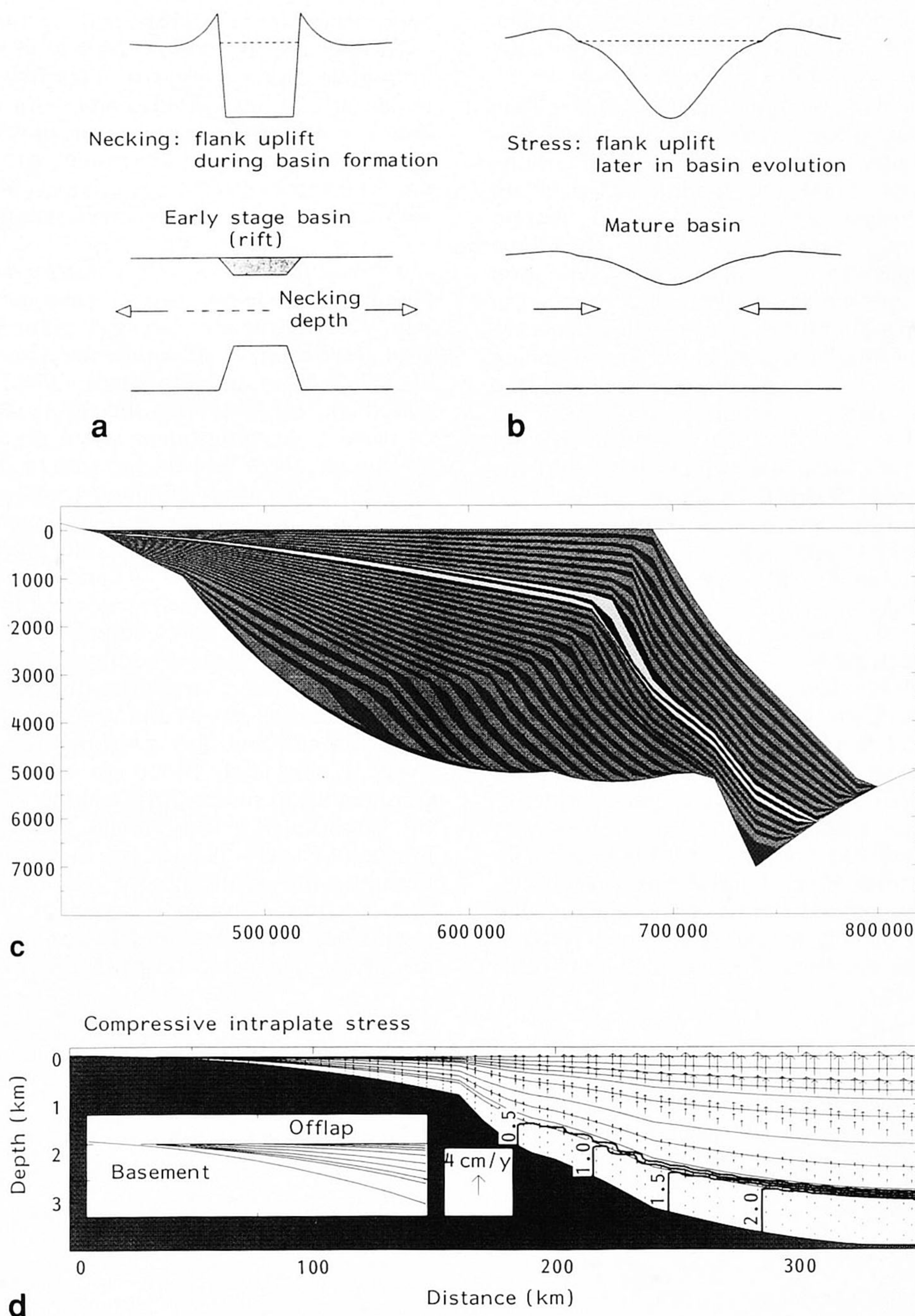


Figure 7 Mechanisms for rapid flank uplift of rifted sedimentary basins and consequences for basin stratigraphy and fluid flow. (a) Necking of the lithosphere during the formation of an extensional basin (Braun and Beaumont, 1989). (b) Stress-induced uplift of basin flanks during the post-rift phase of basin evolution (Cloetingh *et al.*, 1985). (c) Sequence boundaries generated by variations in the level of tectonic stress during the post-rift phase of extensional basins. The model incorporates necking of the lithosphere during the basin formation phase (after Van Balen and Cloetingh, 1994). (d) Hydrodynamic regime and enhanced overpressures in rifted basin during the development of a stress-induced offlap phase (after Van Balen and Cloetingh, 1993)

1993).

A number of features of the geological evolution of the Sverdrup Basin (Canadian Arctic) make it well suited to address a number of the above issues by fully dynamic modelling. These include (1) what appears to be an example of elastic strain recovery immediately at the end of the synrift episode, resulting in mild compressional deformations in the synrift depositional sequences along some of the basin margins (perhaps

depending on orientation to the prevailing stress field) and (2) what appears to be a rapid folding of the entire crustal section, with a wavelength of 200 km, during the intracontinental shortening associated with the Eurekan Orogeny (Stephenson *et al.*, 1990). Additionally, the geometry and geological relationships of third-order stratigraphic cycles are very well documented and this could be an excellent place to test the relative contributions of eustasy and tectonics to the

sedimentary basin record (Embry, 1989).

In extensional tectonic environments, necking and faulting will take place when stresses exceed the lithospheric strength. Numerical modelling is required to integrate the interplay of the various factors that control the record of rifting-induced vertical motions (Bertotti *et al.*, 1993). This is even more true on a longer time-scale, dependent on, for example, the rheological layering and the formation of decoupling zones. Strengthening and healing of the lithosphere might take place during cooling. Numerical modelling has also shown the part played by the depth of necking in the process of basin formation (Braun and Beaumont, 1989; Kooi *et al.*, 1992). More work addressing the inter-relation of lateral variations in depth of necking in rifted basins is required.

In a compressional tectonic setting the effect of stress on foreland basin flexure can be important, in particular when stresses are building up to a threshold on which thrusting takes place (Peper *et al.*, 1992). Future numerical modelling should focus on the interplay between short wavelength brittle tectonics and long wavelength flexural dynamics of the underlying lithosphere. The effect of stresses can be severe on modulating and enhancing the magnitude of the flexural peripheral foreland bulges and might also affect the flexural coupling between foreland basins and neighbouring rifts (Quinlan and Beaumont, 1984).

Outstanding problems in constraining the relation between near-surface deformation and deeper lithospheric processes

The step from kinematic to dynamic models. The past decade has seen the emergence of section balancing as a widely accepted technique for the analysis of extensional basins (Gibbs, 1983). Principles of section balancing were first developed to unravel complex geometries in fold and thrust belts (Dahlstrom, 1969; 1970; Suppe, 1983). The accuracy of a restored section depends not only on the quality of data but also on the validity of the principle of mass conservation adopted in the balancing/restoring process (Moretti *et al.*, 1990; Zoetemeijer and Sassi, 1992; Zoetemeijer *et al.*, 1992). There are several reasons, however, why section balancing, despite its recognition as a valuable tool, is not easily applied to extensional basins. Compaction and the synsedimentary nature of many faults, involving sedimentation and erosion, means that section balancing of the synrift sequence is not straightforward (Nunns, 1991; Westaway and Kusznir, 1993).

Figure 8 provides an example of how numerical and analogue models can provide valuable insights into the geometry and kinematics of faulting (see also Brun and Tron, 1993; Nieuwland and Walters, 1993; Sassi *et al.*, 1993). Figure 8a shows a seismic section from Borneo (Hinz *et al.*, 1989), which shows the association between basin formation and thrusting in a foreland belt. Figure 8b shows that kinematic models which are based on simple geometric principles can reproduce the complex interplay of thrusting, sedimentation and erosion in a compressional foreland belt. Figure 8c shows that analogue models can also reproduce many

of the features shown in the seismic section of Figure 8a.

Although powerful in reconstructing the complexity of near-surface structural evolution, the kinematic models do not address the dynamics of the lithospheric process operating in thrust belts. Of particular importance in this respect is the flexural response of the lithosphere to (sub)surface loading. It is therefore essential to build on the geometrical concepts, with the development of dynamic models to quantify the intrinsic coupling between upper crustal deformation, as manifested in the structure and evolution of sedimentary basins, and lower lithospheric deformation reflecting large-scale regional or global tectonic events.

Subsidence in some classes of basin can be related to lithospheric scale processes occurring as part of the overall plate tectonic paradigm. For example, it is widely accepted that passive margins subside as a result of lithospheric extension (McKenzie, 1978) and that foreland basins are flexural consequences of collision between a continent and outboard terranes (Beaumont, 1981). On the other hand, models for the origin of intracratonic, forearc and transtensional basins are essentially still at cartoon level, involving processes that are difficult to quantify and evaluate (see also Stel *et al.*, 1993, for a discussion).

The natural variability that appears between superficially similar basins has led to the *ad hoc* introduction of increasing complexity into kinematic models. For example, models of extensional basins alternatively assume either pure or simple shear extension or a combination of both. Pure shear models may involve either uniform extension (McKenzie, 1978) or depth-dependent extension (Royden and Keen, 1980). Models incorporating simple shear have invoked a variety of deformation styles, such as whole lithosphere simple shear (Wernicke, 1985) or ramp/flat or domino faulting above a lower lithosphere deforming in pure shear (Gibbs, 1989). The apparent need to introduce such a variety of mechanisms suggests that the lithosphere deforms in a complex variety of modes.

Some progress in evaluating the dynamics of extensional basin formation has been made by finite element models (Dunbar and Sawyer, 1989; Braun and Beaumont, 1989; Bassi *et al.*, 1993) for the simplified rheological structure for the lithosphere. These models allow the examination of how the basic properties of the lithosphere influence the style of deformation and testing of the relative importance of factors such as crustal and mantle weaknesses and geothermal gradients in controlling the style of lithospheric deformation. Figure 9 shows an example of recent finite element modelling carried out to investigate the thermomechanical evolution of the lithosphere during rifted margin formation (Bassi *et al.*, 1993). These models allow the full incorporation of depth-dependent brittle–ductile rheology of the lithosphere and its effect on the style of strain localization and break-up. However, as discussed above, the construction of dynamic models is severely limited by our knowledge of lithospheric rheology. It is obvious that dynamic models have the potential to provide a strong theoretical base for kinematic formulations.

On the other hand, kinematic modelling of high

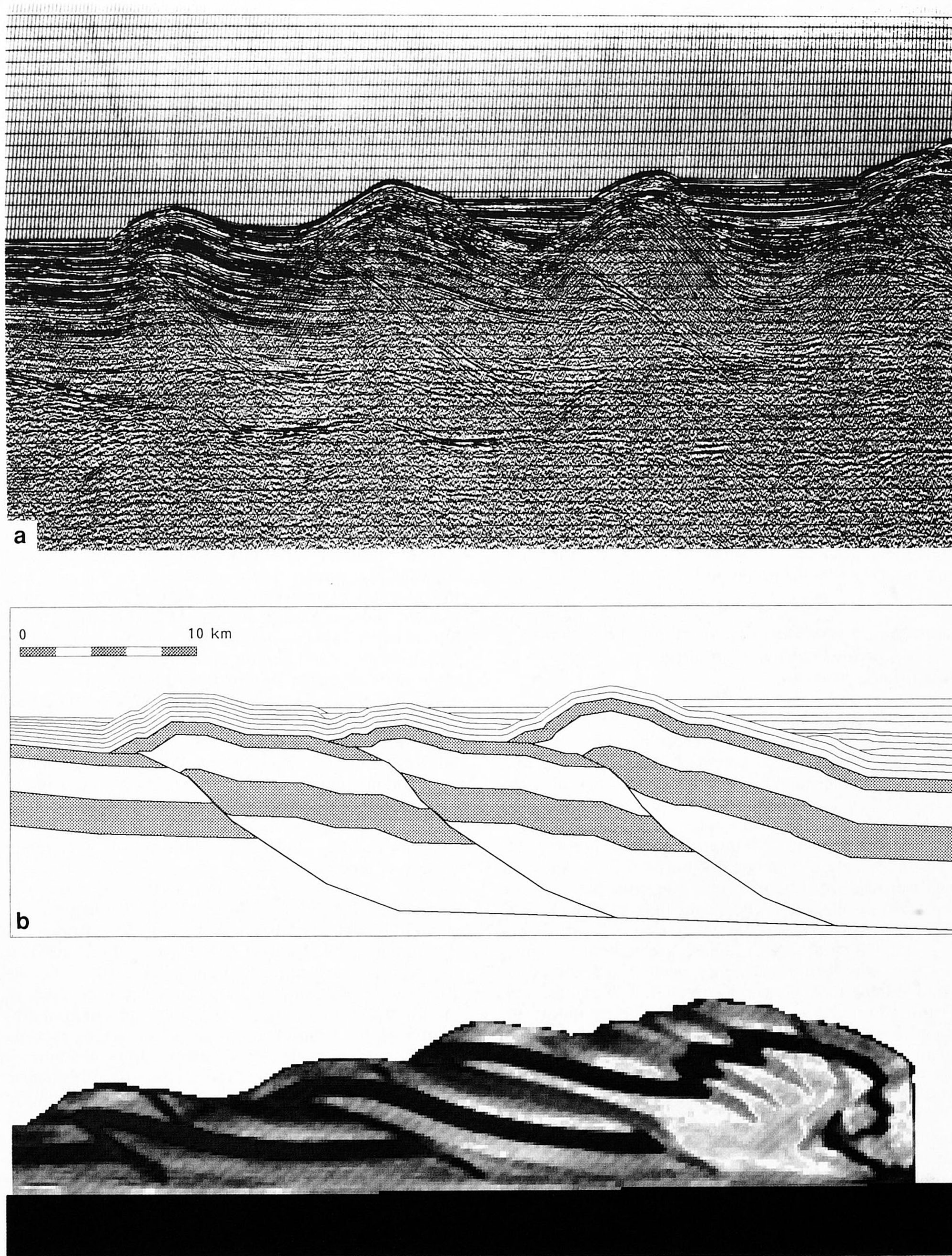


Figure 8 Structural style and basin geometry in a foreland fold and thrust belt. (a) Seismic section from Borneo (Hinz *et al.*, 1989) displaying basin formation during tectonic development of thrusting. (b) Result of kinematic modelling, based on geometrical principles, to reconstruct the complex interplay of thrusting, sedimentation and erosion (Zoetemeijer *et al.*, 1993). (c) Result of sandbox experiment imaged by X-ray tomography (after Colletta *et al.*, 1991)

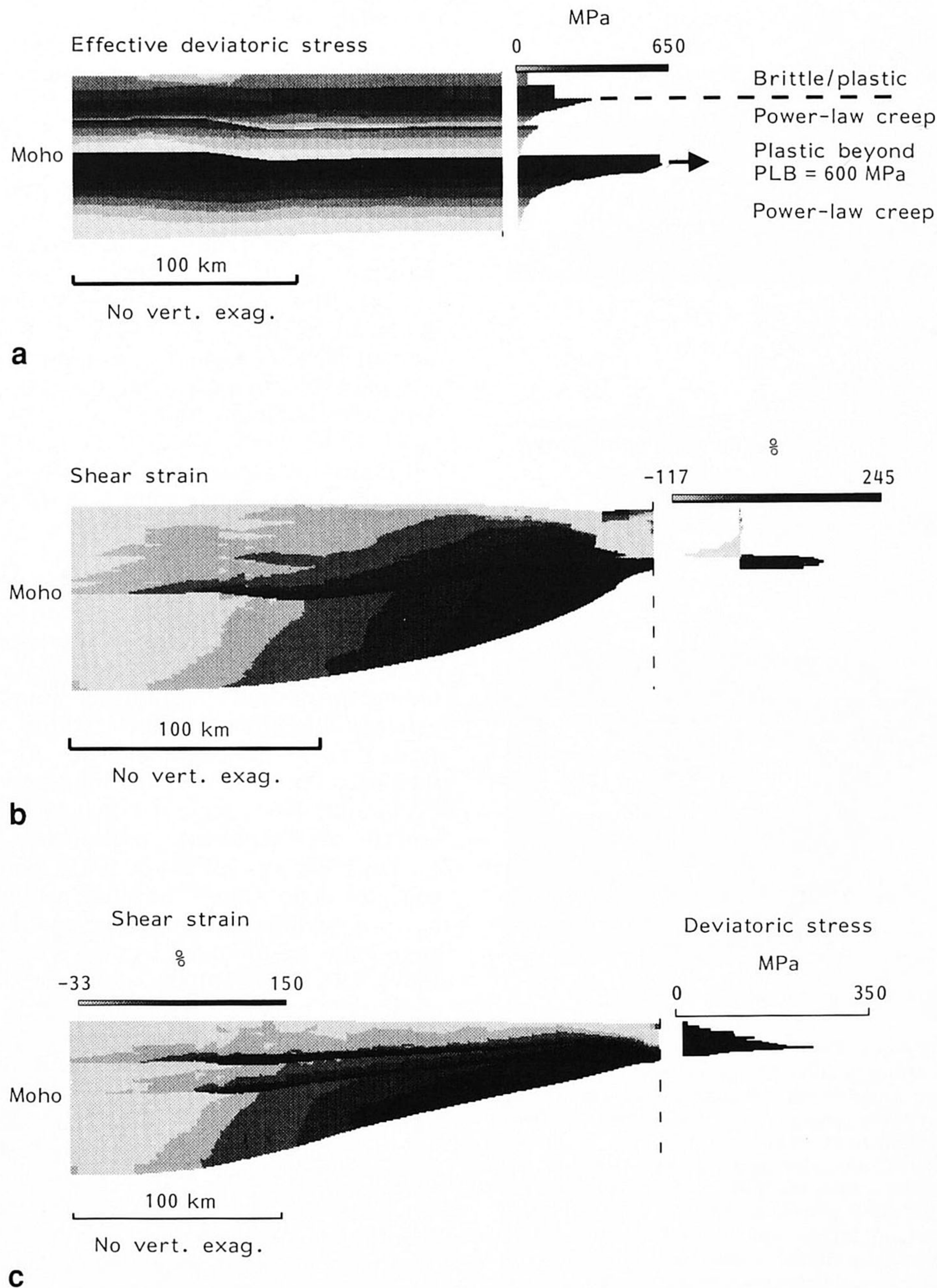


Figure 9 Dynamic models of extensional basin formation illustrating the role of rheological control on the style of rifting. (a) Rheological stratification and effective lithospheric distribution predicted for a model of dry lithospheric rheology, based on extrapolation of rock mechanics data, incorporating plastic instabilities. The right-hand side of the figure shows the distribution of strength and deformation mechanisms at different crustal and lithospheric levels. (b) Deformation and shear strain patterns predicted by the model displayed in Figure 9a after 42 km of extension. Right-hand panel shows distribution of shear strain with depth. Note the development of a high-shear strain zone in the lower crust. (c) Modelling predictions for model with wet lithospheric rheology after 91 km of extension. Note the pronounced differences in the predicted styles of extension due to differences in adopted rheologies for the lithosphere underlying the rifted basin (after Bassi *et al.*, 1993)

quality data sets from rifted basins can yield important constraints on dynamic models for extensional basin formation. Over the last few years these kinematic models have provided a robust framework for the quantitative analysis of basin stratigraphy and associated vertical motions in rifted basins (Aigner *et al.*, 1990; Kusznir *et al.*, 1991; Kooi *et al.*, 1992). Whereas backstripping techniques are widely used to analyse tectonic subsidence data and basin fill

(Angevine *et al.*, 1990), the quantification of uplift and erosion dynamics has proved to be more difficult (Garfunkel, 1988). Advances in fission track thermochronology now enable it to test the predictions of forward models, providing an independent constraint on parameters such as the level of lithospheric necking (Figure 10; see also Van der Beek *et al.*, 1994).

Another frontier is the ongoing development of

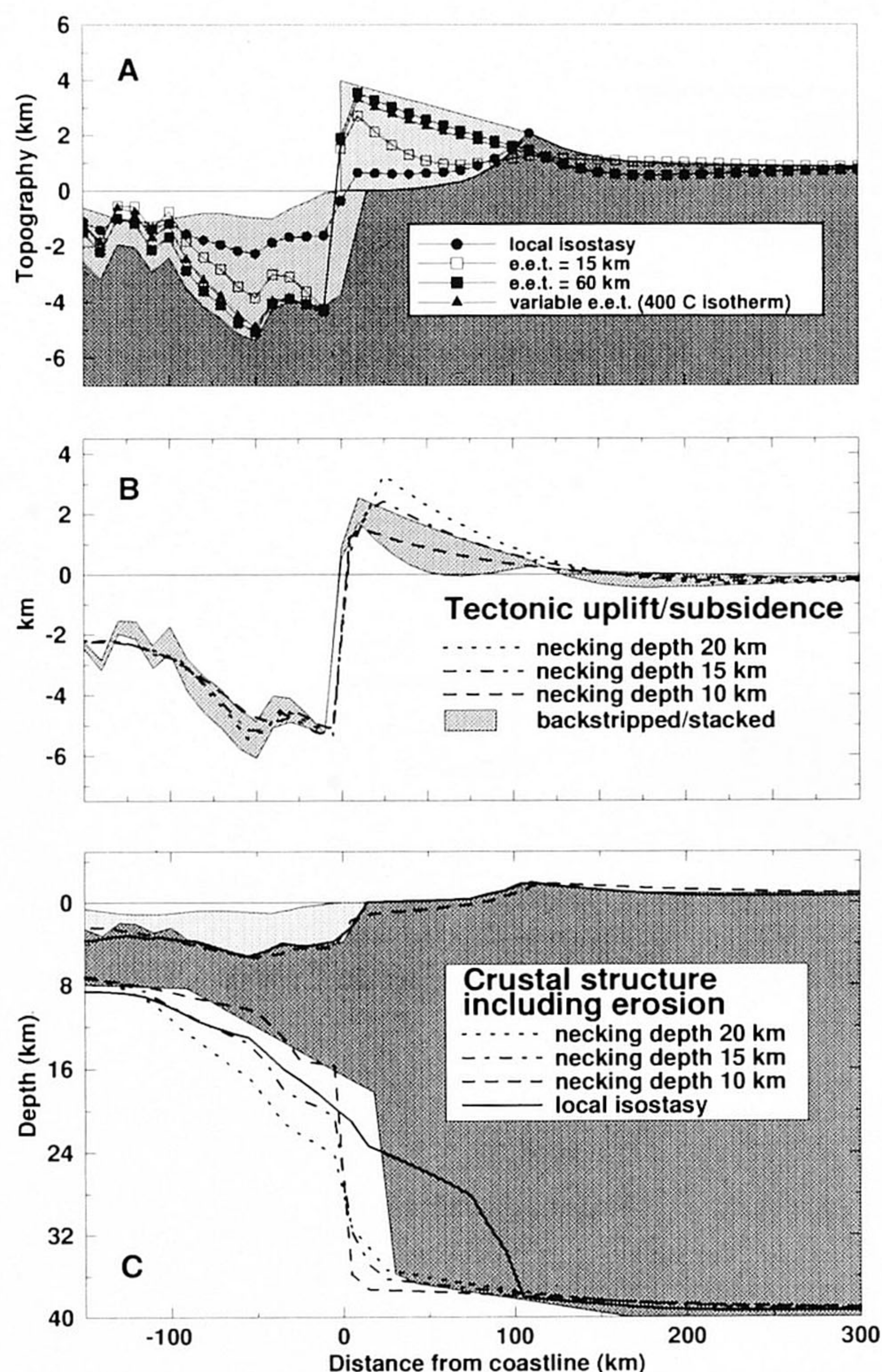


Figure 10 Kinematic modelling of rift shoulder topography and associated vertical motions constrained by fission track data. (A) Backstacked tectonic uplift and subsidence patterns at Saudi Arabian Red Sea margin. Shading denotes eroded rift flank constrained by fission track data and resulting basin fill constrained by seismic reflection data. (B) Modelled tectonic uplift and subsidence patterns for different kinematic models, characterized by different levels of necking. Shaded band denotes backstacked uplift/subsidence. (C) Crustal structure configuration predicted by model shown in Figure 10B and comparison with Moho configuration inferred from seismic refraction data. After Van der Beek *et al.* (1994)

numerical procedures to allow the incorporation of faults into three-dimensional models of large-scale flexural deformation of the lithosphere. Figure 11 shows a comparison of observed basin configuration and three-dimensional modelling of the upper crustal response to extensional basin formation for the northern segment of the Lake Tanganyika (Van Wees and Cloetingh, 1994). The models support the notion of low e.e.t. values for upper crustal flexure inferred from two-dimensional flexural cantilever models (Kusznir *et al.*, 1991; Kusznir and Ziegler, 1992). The apparent inconsistency of the predictions of these models with high e.e.t. values inferred from modelling studies constrained by gravity data (Ebinger *et al.*, 1991) is probably caused by the decoupling of crustal and subcrustal lithosphere facilitated by the presence of a relatively ductile lower crustal level (Van Wees and

Cloetingh, 1994).

Very little work has been carried out on dynamic models of compressional tectonics. Jamieson and Beaumont (1989) and Willett *et al.* (1993) have used such techniques to investigate large-scale deformation within compressional orogens and to relate this deformation to metamorphism and the uplift history of near-surface rocks. To evaluate such models considerable information is needed on the variation in metamorphic grade and cooling ages as a function of distance from an orogen. Field studies such as those described by Kamp *et al.* (1989) from the Southern Alps of New Zealand are important for studying the dynamics of compressional orogeny. The Southern Alps area is among the world's best because of the rapid uplift and good exposures. Deep seismic reflection data across the area would be particularly welcome in providing a glimpse of the internal structure of an actively deforming orogen.

Sedimentological influences on basin evolution.

Although the success of any individual basin model is often gauged by its ability to reproduce the observed sedimentary record, few models deal realistically with sediment transport and preservation. For example, patterns of unconformities within foreland basin stratigraphy that have been attributed to the rheological behaviour of the lithosphere (Quinlan and Beaumont, 1984) may in fact be related to neglected aspects of sediment transport (Flemming and Jordan, 1989; Sinclair *et al.*, 1991). Sediment transport and post-depositional alteration within the basin also have a significant influence on the evolution of large-scale basin architecture through time (Watts, 1989). This is true both because the sediment load itself modifies basin subsidence and because the post-depositional compaction and diagenesis of sediment affects the accommodation space available for additional sediment (Schlager, 1993). As sediment transport can be modelled to first order as diffusional processes dependent on local topography (Kenyon and Turcotte, 1985; Flemming and Jordan, 1989; Peper *et al.*, in press), such effects can be incorporated into quantitative basin models. The modelling of erosion dynamics requires more sophisticated approaches (Kooi and Beaumont, 1994) and will continue to be a topic of frontier research during the next few years.

Limits imposed by our current understanding of the lower lithosphere. The more deep seismic reflection data are gathered, the more diversity appears in the reflection patterns obtained. However, some patterns appear often enough to demand explanation by even first-order models of lithospheric deformation (Quinlan *et al.*, 1993). Frequently seen features include: dipping reflectors in the upper crust that can often be traced into mapped faults or shear zones and are, therefore, considered to represent faults or shear zones themselves; subhorizontal bands of reflectivity in the middle or, more commonly, in the lower crust; and dipping reflectors that appear to cross-cut the base of the crust and extend a short distance into the upper mantle. Occasionally these latter reflectors can be traced to greater depths, as with the BIRPS data north and west of Britain (Warner and McGeary, 1987).

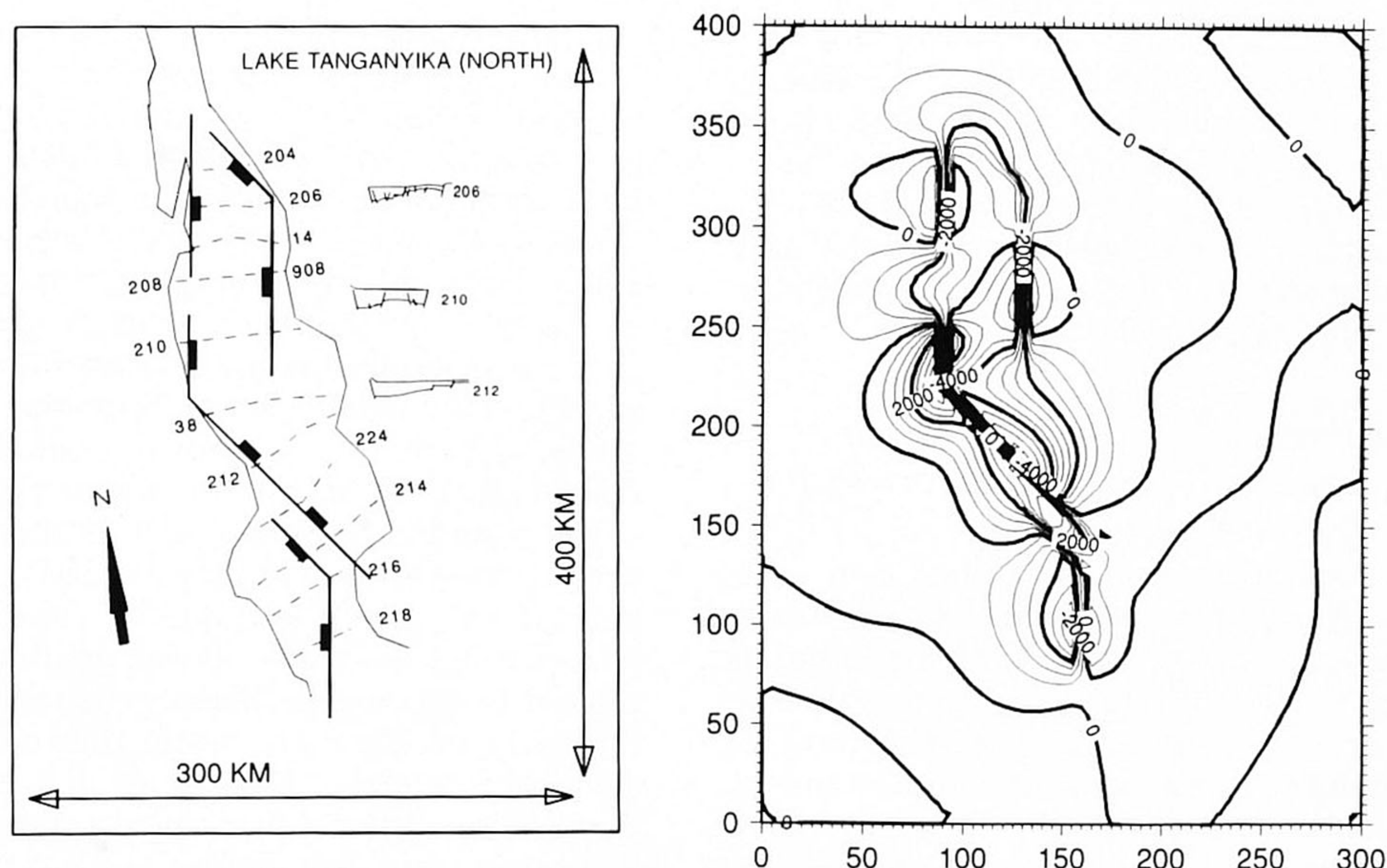


Figure 11 Three-dimensional model of crustal flexure incorporating planar faults for northern segment of Lake Tanganyika. Left: observed basin geometry and main boundary faults inferred from seismic reflection profiles (location indicated by broken lines). Also shown are top-sediment and top-basement reflectors of three seismic sections. Right: three-dimensional modelling results. Deflection patterns are in good agreement with observed basin geometry for an η value of 5 km. Deflection contour intervals are 500 m. Steep gradients in the predicted deflection correspond to the location of main boundary faults. Horizontal and vertical scales give distances in km. After Van Wees and Cloetingh (1994)

Deep reflectors on seismic profiles are often interpreted as lithospheric detachments marking major changes in the orientation and possibly style of deformation (Keen *et al.*, 1987). These detachment surfaces are essential components of simple shear extension models in which they are expected to link offset, dipping faults or shear zones (Gibbs, 1987). Lower crustal reflectivity is generally attributed to one or more of three causes: fluid-filled pore space; lenticular mafic intrusions; or shearing within the lower crust. High pressure rocks exhumed from lower crustal depths are characteristically granulite facies anhydrous mafic silicates in which primary lithological layering has often undergone ductile shearing. Interestingly, such reflectivity patterns are not as obvious in near-surface granulite terranes exhumed from lower crustal depths (Klemperer *et al.*, 1986). This suggests that the reflectivity of the lower crust is at least partially controlled by other, *in situ*, factors that do not survive transport to the surface. The presence of fluid layers in the lower crust (Touret, 1992) is often invoked to explain both the seismic reflectivity pattern and the high electrical conductivity inferred for some regions of lower crust (Hyndman, 1988). The existence of fluids in the deep crust is a controversial topic, however, as they are difficult to reconcile with the dry mineralogy of granulite facies rocks. The true significance of lower crustal reflectivity is obviously fundamental for an understanding of lithospheric deformation.

Dipping reflectors in the upper mantle are important elements of various tectonic models for extension and compression. They may, for example, represent the subcrustal portion of shear zones in simple shear models of lithospheric extension (Wernicke, 1985). Alternatively, they may record shortening of the upper lithosphere above a delamination surface in the late stages of continent–continent collision (Stockmal *et al.*,

1986). Subhorizontal reflectors in the mantle (Lie and Husebye, 1994) are even more ambiguous (Figure 3). Do they have a structural meaning? Are they indicators of strain distribution in the mantle? What is their age? What is the role of melting and/or fluids with regard to these reflectors? Answers to these questions require more data on the fine structure of the subcrustal lithosphere. Important questions also remain about the effects of non-conservative processes, such as partial melt diffusion and mantle–crust interaction, on crustal geometry, mechanical behaviour and thermal regime. Dynamic models suggest that these are important considerations for the ultimate behaviour of an extending region.

Well-known controversies exist about discrepancies from estimates of crustal stretching and lithosphere extension (Ziegler and Van Hoorn, 1989; Burrus and Audebert, 1991; Ziegler, 1992). Important questions relate to whether these discrepancies reflect differences in upper and lower crustal attenuations resulting from destabilization and upward displacement of the Moho discontinuity during rifting. The density of the data in areas such as the North Sea allows in principle the testing of models and concepts on basin modelling linking lithosphere scale to subbasin scale (Kusznir *et al.*, 1991) as well as of three-dimensional models developed to link flexure and faulting (Van Wees and Cloetingh, 1994).

Similar questions play a central part in discussions on subsidence mechanisms of basins located in the former USSR. Whereas, for example, earlier work on the West Siberia Basin has suggested a discrepancy between observed crustal thicknesses and predictions of thinned crust by the McKenzie stretching models for basin formation (Artyushkov and Baer, 1990), backstripping analysis supports an important thermal control on the tectonic subsidence record (Lobkovsky

et al., submitted).

In this respect a better understanding of the scaling properties of fault populations is required from reflection seismic data on a regional scale (Walsh *et al.*, 1991; Gillespie *et al.*, 1993). Areas such as the North Sea, Gulf de Lions, East Greenland and Gulf Coast provide interesting sites for further investigation in a relatively well defined geological context.

The role of structural and transient non-linear elements in lithospheric dynamics in the origin and evolution of sedimentary basins

Experimental data provide constraints on the behaviour of rocks at high strain rates and on a small-scale, whereas outcrop studies, high resolution seismic and deep reflection/refraction seismics provide vital data covering a wider range of scales, both in terms of strain rate and dimensions. The understanding of the dynamics of sedimentary basins is hampered by our present inability to integrate these different scales associated with the intrinsic heterogeneity of the deformation within sedimentary basins and the underlying lithosphere.

Analogue modelling is one possible approach for sedimentary basin analysis and has been extensively used (Vendeville and Cobbold, 1987; Colletta *et al.*, 1991; Brun and Tron, 1993; Cobbold *et al.*, 1993). Such an approach provides valuable information on the spatial and temporal relationships of some geological structures. However, due to scaling problems, inhomogeneity, and the importance of thermal activation on the actual deformation, such an approach will benefit from a coupling with numerical modelling studies to elucidate the driving physical mechanisms of sedimentary basin evolution.

Localization phenomena, heterogeneous materials and fractures are beginning to be incorporated in numerical models. Important in this respect is the simulation of mechanical and thermal properties in strongly heterogeneous continental lithosphere at different scales, which has not yet received full attention. The basin formation processes can be formulated through well established balance principles of thermomechanics, with the physical processes explicitly described by differential equations. With more rapid progress in distributed computing power and non-linear simulation of rheological behaviour, quantitative analysis incorporating these elements in predictive numerical models of basin evolution is now within reach.

Modelling of spatial and temporal variations in rheology in the upper parts of basins. Spatial variations of rheological properties are likely to be extremely important in controlling the localization and style of deformation. The primary control on spatial variations of rheological properties are the compositional changes associated with the tectonic evolution of an area. A widely observed phenomenon is the tendency for localized deformation to repeatedly occur in certain places over geologic time — often with different structural styles. For example, both the New Madrid Rift and Rhine Grabens are intraplate extensional structures that are currently being

compressionally reactivated with the predominant style of contemporary faulting in both areas being strike-slip (Ziegler, 1992).

A characteristic of many models of sedimentary basin formation, such as domino and listric fault models (Wernicke and Burchfiel, 1982; Angelier and Colletta, 1983), is that deformation is taken to be accommodated within the upper crust by brittle structures (simple shear) and within the lower crust as plastic flow (pure shear). Although these assumptions are geologically naive, current models provide valuable insights into deformation, at least on the large scale.

Deep seismic profiles [such as the BIRPS profiles, see Klemperer and Matthews (1987) and Klemperer and Hobbs (1991)] suggest the existence of different and decoupled modes of deformation, which can be related to rheological heterogeneities. Low values for estimates of effective elastic thickness from flexural cantilever models (Kusznir *et al.*, 1991) as well as observations from thin-skinned tectonics indicate that the lithosphere can deform in a variety of modes, decoupled by horizontal low strength.

More realistic models need to take account of, for example, the heterogeneous nature of strain within the basement, taking the form of discrete shear zones often representing the downward continuation of faults (Gibbs, 1987; Jackson, 1980; LePichon and Chamot-Rooke, 1991) and the fact that deformation of the upper crust can be plastic and on certain scales of observation comprises significant ductile deformation.

The applicability of the Mohr–Coulomb criterion of failure to fault formation within the upper crust (Mandl, 1988; Zoback and Zoback, 1989, 1991) is widely accepted, although it provides only an empirical basis for the formation of faults. The question of localization of faults is less well understood and requires a better understanding of the formation and nature of microcrack arrays and the basic control imposed by various parameters, e.g. porosity, the heterogeneous distribution of elastic properties and strength and spatial and temporal variations in fault size distributions. Progress can be made on various fronts, including (i) the development of fracture mechanical models, incorporating finite element methods, (ii) experimental work, incorporating microseismic monitoring (e.g. Main *et al.*, 1990), (iii) seismological studies and (iv) geological analysis. The significance of fault populations in terms of their effect on bulk properties has not been fully addressed and the uses and limitations of finite element models of faulted lithosphere need to be assessed with the incorporation of strength characteristics of faults and significant ranges of discontinuities (i.e. fault size) (Melosh, 1990; Beekman *et al.*, submitted; Sassi *et al.*, 1993).

Simple models for the rheology of the upper crust using Byerlee's friction law and assuming a hydrostatic pore pressure gradient give a lower limit of strength of the lithosphere consistent with measured stress levels in the uppermost crust (ca. 5 km) as well as focal depths of earthquakes and the thickness of the seismogenic layer. Factors affecting the frictional properties of faults include the roughness of the slip surface, pore fluid pressures and the presence of gouges, breccias and clay smears. A better understanding is required of the impact of these factors on fault strength at a variety of

conditions (e.g. different loads and for different amounts of slip). For example, an ubiquitous feature of sedimentary basins is the presence of overpressured zones below the isolation depth. Further development of time dependent compaction models is crucial for the simulation of pore fluid pressure variations with depth in sedimentary basins (Schneider *et al.*, 1993). Mechanical models describing the interplay between fault movement and pore fluid pressure gradients in the crust need further attention, particularly with regard to seismic pumping, fault valving activity and hydraulic fracturing (Sibson, 1981; 1990; Carrigan *et al.*, 1991).

Current models describing the growth of faults (Walsh and Watterson, 1988; Scholz and Cowie, 1990; Gillespie *et al.*, 1993) are empirically based and mechanical models are required which provide a basis for fault growth in terms of cumulative displacement and fault size. The scale dependence of elastic dislocation versus flexural isostatic fault models has received some attention (King *et al.*, 1988; Ma and Kuszniir, in press; Roberts and Yielding, 1992), but temporal and spatial considerations, particularly with regard to strain rate, are likely to require refinement. The development of mechanical models describing the

interaction and coalescence of faults should be complemented by the analysis of the kinematic evolution of fault systems, particularly in basins containing thick sequences of synrift sediments; in such areas it should be possible to establish the rates of movement on major faults and the spatial variations in bulk strain rates. Of particular importance for our understanding of inversion tectonics (Ziegler, 1987) is the effect of strain rate on the formation of new faults versus the reactivation of inherited weakness zones (Knipe, 1985).

In sedimentary basins subhorizontal heterogeneities, such as salt layers and some overpressured shales, play a significant part in basin deformation and offer challenges to the modelling of basins (Last, 1988). Low angle normal faulting and detachments often occur along salt and shale layers, providing an important influence on the structural style of overburden deformation; numerical models are being developed (e.g. Van Wees and Cloetingh, 1991; *Figure 12*) to integrate these phenomena. Little is known of how ductile layers transmit fault-controlled extension of basement to the cover sequences or how such layers react to differential loading by uneven sedimentation

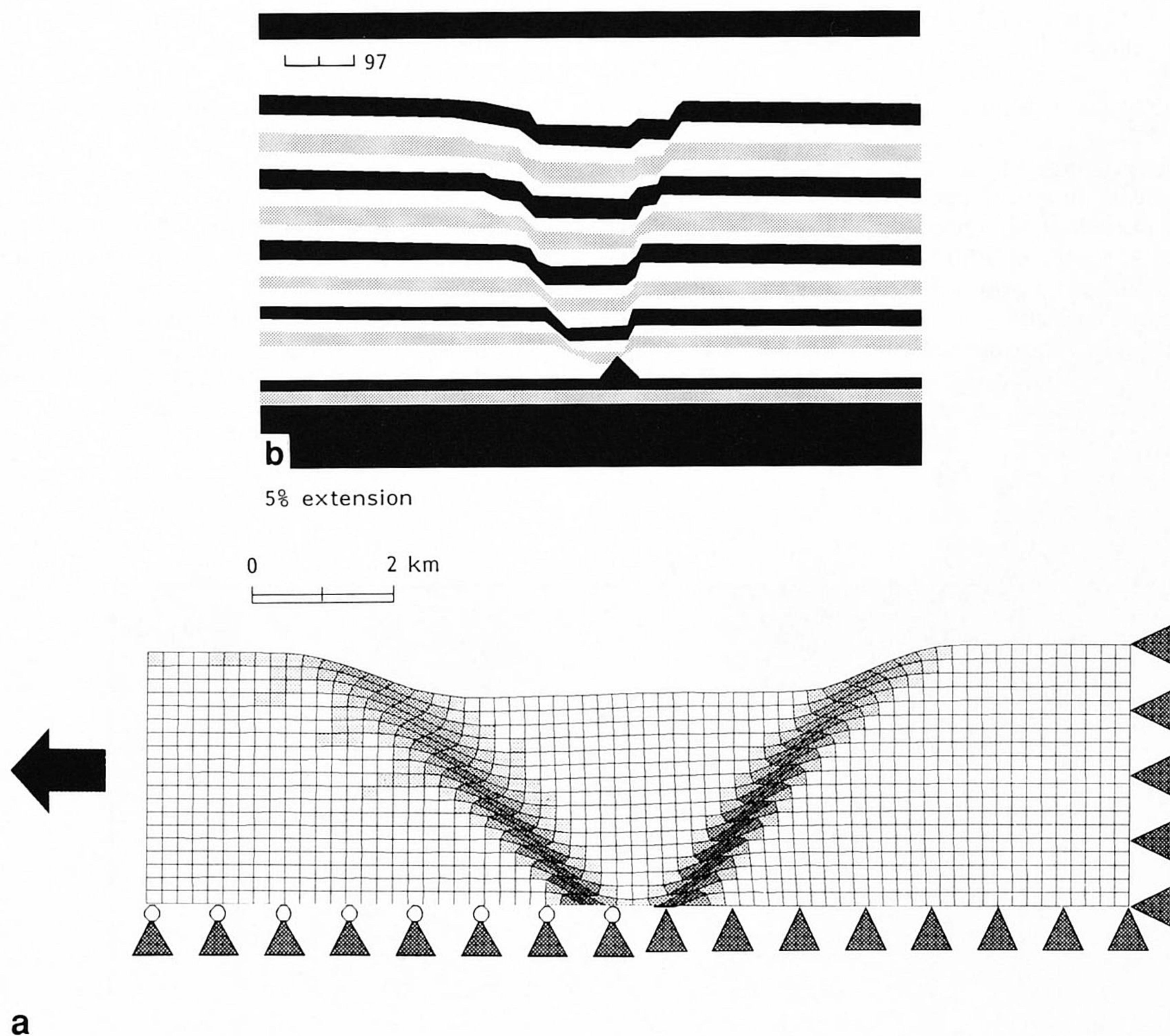


Figure 12 Décollement controlled extensional faulting at basin scale. (a) Results of numerical simulation. Displacements magnified by a factor 50. Hangingwall displacements induce tensional stresses which concentrate at dipping low strength interface (open circles) and lead to failure. Grey shading denotes amount of effective plastic strain corresponding to 50 m of effective displacement. After Van Wees and Cloetingh (1991). (b) Results of analogue modelling of fault displacement above a linear dislocation. After McClay and Ellis (1987)

(Jenyon, 1986), which is limiting our understanding of the relation between large-scale tectonics and detailed basin geometry and evolution. In fact, more precise knowledge of the geometry and structural evolution of areas containing evaporite–clay layers may shed light on the behaviour of brittle–ductile–brittle layered systems in general. Field areas where such observations can be made are the Sverdrup Basin of Arctic Canada (Stephenson *et al.*, 1992), the Prebetic Zone of south-east Spain and the Dead Sea Basin. Evaporite structures in the Sverdrup Basin and in the Dead Sea Basin (Ten Brink and Ben-Avraham, 1989) are both well exposed and particularly well preserved by the dry climate (Schwerdtner and Osadetz, 1983).

Modelling of the ductile mode of deformation in deeper parts of basins and underlying lithosphere. At greater depths, within the semi-brittle or ductile regimes of the crust, temperature, strain rate and rock type all affect the creep properties of the crustal materials. The rate of subsidence, lower crustal strain and flank uplifts (Figures 7a and 10) reflect the interaction of lithospheric mass and heat transfer, isostasy and flexure during basin formation (Braun and Beaumont, 1989; Kooi *et al.*, 1992).

Ductile modes of deformation (as for the brittle mode) depend on a number of parameters such as fluid pressure, chemical effects (associated with those fluids), grain sizes and shapes, as well as on microstructural instabilities such as phase change, recrystallization and grain growth. Furthermore, the ductile behaviour of a polycrystalline aggregate depends on its chemical composition and its different stable mineralogical phases. Extrapolation of experimental results in both time and space is therefore hazardous without a proper knowledge of the different physical mechanisms of each phase. Uncritical extrapolation of experimental data can lead to a simple but tractable view adopting a homogeneous and stable mode of deformation, in contrast with evidence from

exposed lower crustal rocks and seismic reflection studies showing the heterogeneous and localized nature of ductile deformation.

The available experimental data represent a great variety of aggregates, microstructures, and environmental parameters. At the same time experimental rock mechanics data have to be extrapolated over several orders of magnitudes in strain rate to be adopted in basin modelling studies. Explicit in these models is the presence of crustal and mantle strong and weak layers (Carter and Tsenn, 1987); stress is partitioned into the strong layers and strain into the weak deformation (Beslier and Brun, 1991).

Most current numerical models (e.g. Jamieson and Beaumont, 1989) treat the lithosphere underlying basins as an elasto-plastic material with a yield strength which varies with depth according to Byerlee's law. Brittle failure is thus approximated as plastic yielding and the deformation that occurs in reality on systems of discrete faults is averaged over a large area of permanent deformation. This model provides a description for the mechanical behaviour of the upper part of the lithosphere, but does not address the details of deformation on a full lithospheric scale.

It is well known that increasingly narrow zones of deformation can develop even in initially continuous bodies depending on the detailed structure of the constitutive relations or interface properties. Localization processes do occur in brittle, ductile modes but also in brittle–ductile transitional zones. Methods for detecting these localizations are undergoing active developments. However, a few studies have been carried out for geological materials and further development is needed to follow such localization phenomena in terms of constitutive and numerical modelling.

To investigate faulting and plastic flow behaviour of the lithosphere on geological time-scales, large strain analysis is required. For large strain problems, a Lagrangian description provides good numerical

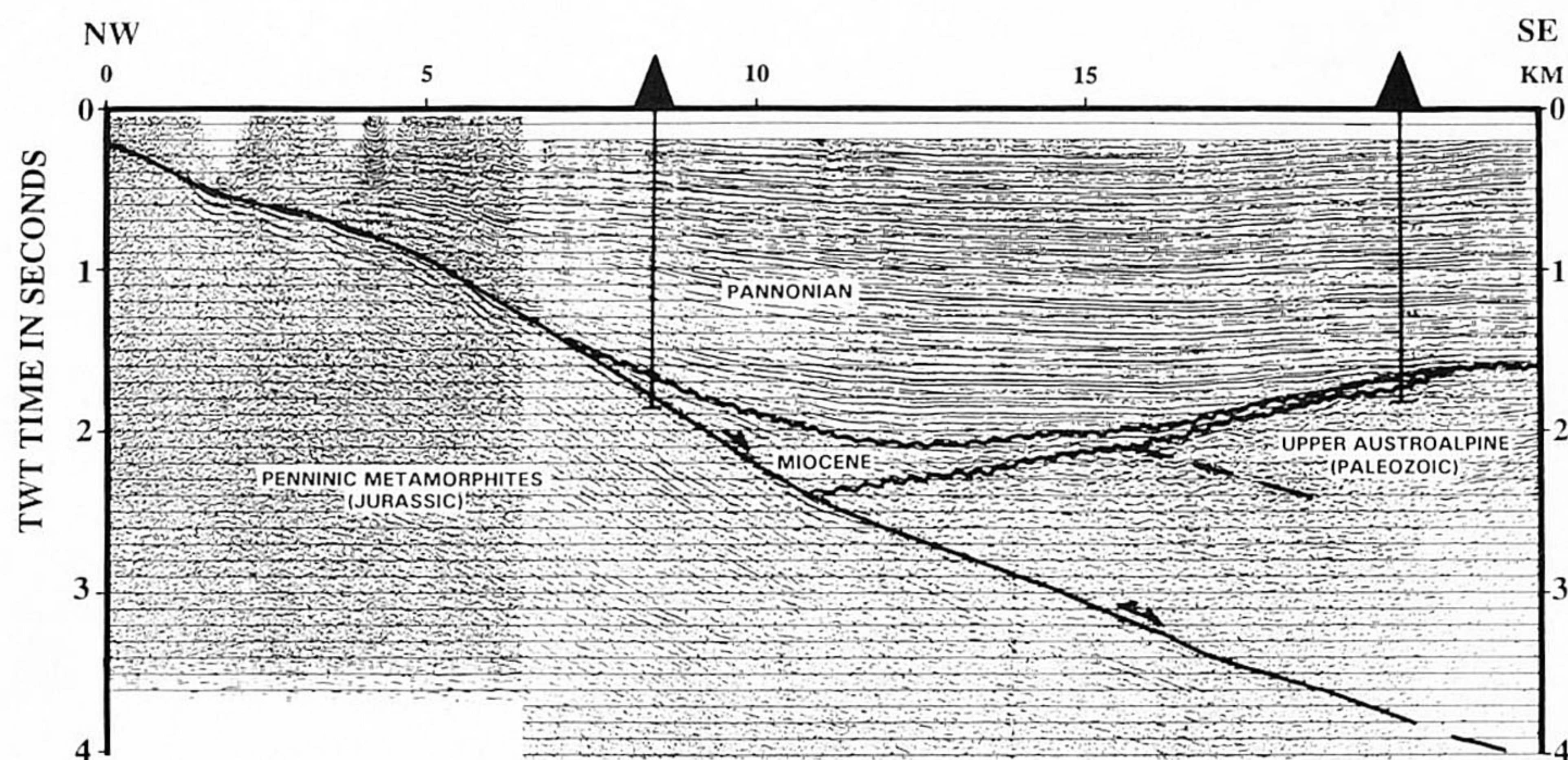


Figure 13 Interpretation of migrated seismic section. The metamorphic basement on the north-western side of the section represents the subsurface continuation of Mesozoic rocks outcropping in the Penninic window of Rechnitz. The low angle tectonic contrast between this unit and the Palaeozoic rocks (sampled by the well on the south-eastern side of the profile) corresponds to a Cretaceous major thrust plane, which was reactivated during Middle Miocene times as an extensional detachment fault, with uplift of the Rechnitz's metamorphic core complex and the development of the asymmetric Neogene basin. After Tari *et al.* (1992)

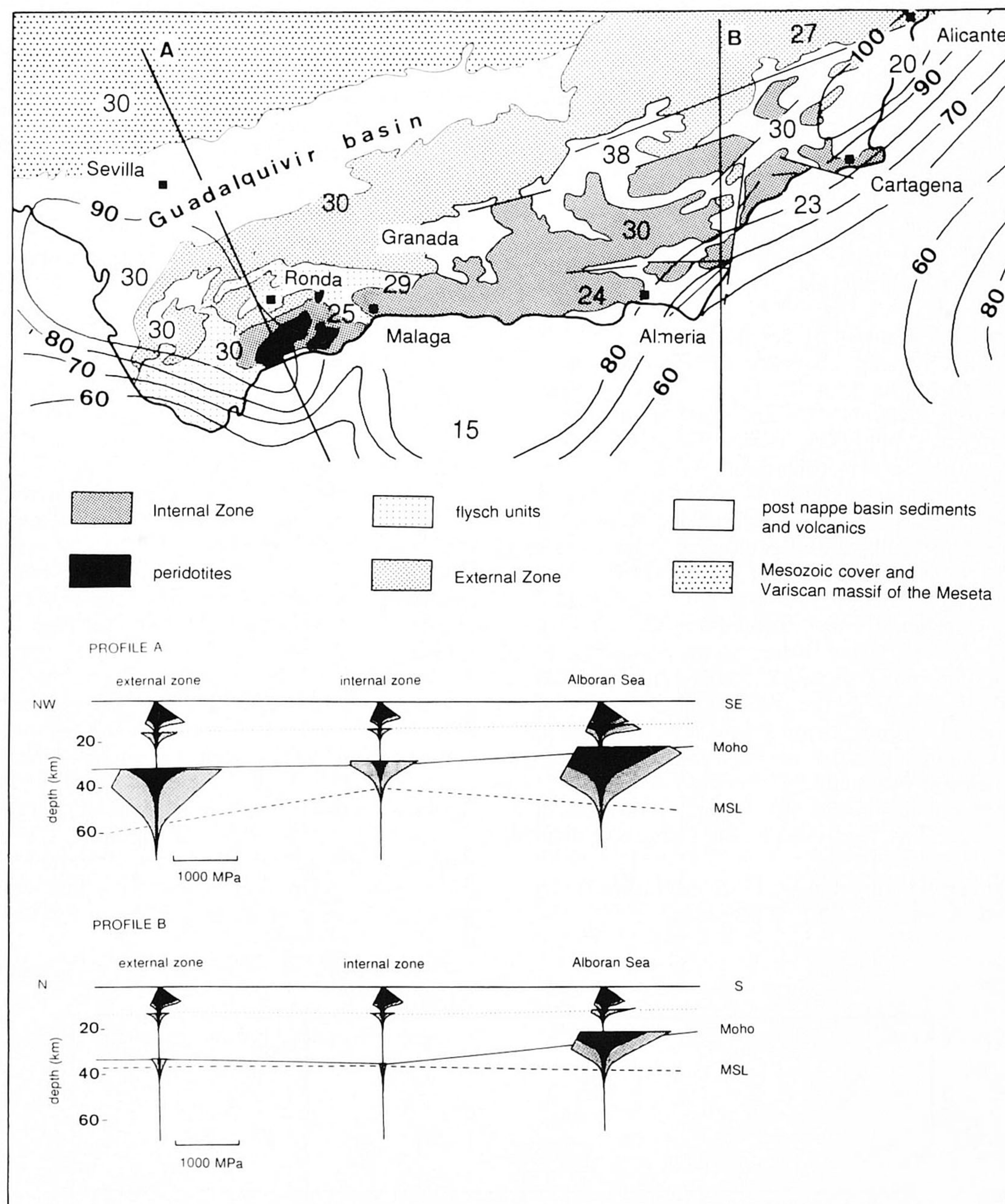


Figure 14 Lateral variations in estimates of lithospheric strength in the Betics/Alboran region obtained from extrapolation of rock mechanics data. After Van der Beek and Cloetingh (1992), Cloetingh *et al.* (1992)

accuracy for history-dependent material, but cannot adequately handle large flow. The Eulerian description, on the other hand, can treat large flow, but it is difficult to account for history dependence or moving boundaries and interfaces. For both descriptions (adaptive) remeshing (Lohner, 1989) is an important tool for future modelling. In this way badly shaped elements can be eliminated in the Lagrangian description, whereas moving boundaries and interfaces can be traced accurately in the Eulerian formulation. Furthermore, adaptive remeshing can be used for detailed analysis of localization and growth of faults (Mandl, 1988) and shear zones.

Localization phenomena in heterogeneous materials are beginning to be incorporated in numerical models

(Chery *et al.*, 1991; Burg *et al.*, 1992; Daudré and Cloetingh, in press; Bassi *et al.*, 1993; Leroy and Molinari, 1993). The identification of the scale at which mechanical and thermal properties have to be formulated is the main challenge, in particular for strongly heterogeneous structures in the continental lithosphere (Dupin *et al.*, 1993).

Apart from spatial variations in rheology, important temporal changes in rheology are associated with the intrinsic polyphase history of most basins (see Figure 13 for an example from the western rim of the Pannonian Basin). For example, foreland basins are often located on the sites of previous rifted basins and continental rifting tends to be localized near the site of earlier compressional orogens. However, most models adopt a

homogeneous starting configuration for the lithosphere and little attention has been paid to how the thermomechanical history of an area affects basin localization and development (Stockmal *et al.*, 1986; Buck, 1991). These effects can be studied in the Betics of south-east Spain (Van der Beek and Cloetingh, 1992) and the Ebro and Aquitaine basins flanking the Pyrenees (Zoetemeijer *et al.*, 1990; Chery *et al.*, 1991; Desegaulx *et al.*, 1991), where basins of extensional and compressional style have alternated on time-scales short compared with thermal relaxation time of the lithosphere.

The Ebro and Aquitaine foreland basins have been studied in detail by deep seismic profiling carried out in the framework of the ECORS Project. As a result, good control is available on the deeper structure, whereas intensive fieldwork (Puigdefabregas *et al.*, 1992) has resulted in firm constraints on the timing of the tectonosedimentary evolution and the geometry of the near-surface structural configuration. Refraction seismic lines and a substantial geological database are available to constrain modelling of the Betics and additional deep reflection profiling has been carried out. These foreland basins formed on the sites of pre-existing rifted basins offer good prospects to quantify the thermomechanical effects of rift-inherited lithospheric heterogeneity on foreland basin evolution. At the same time, their location adjacent to offshore areas of extension allows the investigation of the effects of coeval flexural interaction (Cloetingh *et al.*, 1992) between foreland basins and rifts on vertical motions in intermediate areas as, for example, the Catalan Coastal Range.

The Western Mediterranean Gulf de Lions Basin (Burrus and Audebert, 1991; Kooi *et al.*, 1992), the

Valencia Trough (Banda and Santanach, 1992; Janssen *et al.*, 1993) and the Alboran Sea (Maldonado, 1992) and the Pannonian Basin (Horvath, 1993) offer a natural laboratory to study the dynamics of extensional basin formation in a regime of overall convergence of colliding continental plates (e.g. Cloetingh *et al.*, 1992). The marine geophysical data of the western Mediterranean basins can be integrated with an extensive onshore data set consisting of deep seismic refraction lines as well as high quality field data on the tectonostratigraphic evolution of the Iberian plate.

Strength envelopes constructed by extrapolation of rock mechanics data for the Alboran/Betic region (Figure 14; see Van der Beek and Cloetingh, 1992; Cloetingh *et al.*, 1992) show important spatial variations in rheological properties reflecting lateral variations in the mode of extension in the Alboran Sea. The strength profiles also support a recent migration of basin extension from the Alboran Sea to the weak lithosphere of the Internal Betics, leading to the formation of pull-apart basins. The subsidence record (Cloetingh *et al.*, 1992) deviates strongly from predictions of standard pull-apart models, cast in terms of lateral heat transport (Pitman and Andrews, 1985), showing the need to incorporate upper crustal mechanics. A succinct feature of the subsidence record is the occurrence of a Pliocene phase of rapid uplift, recently recognized for the whole eastern Iberian margin (Figure 15; Janssen *et al.*, 1993). The timing and large-scale nature of the observed tilting and uplift supports an interpretation in terms of slab detachment inferred from seismic tomography (Wortel and Spakman, 1992). Another outcome of the modelling of the basin formation processes in the western Mediterranean region, in particular for the Valencia

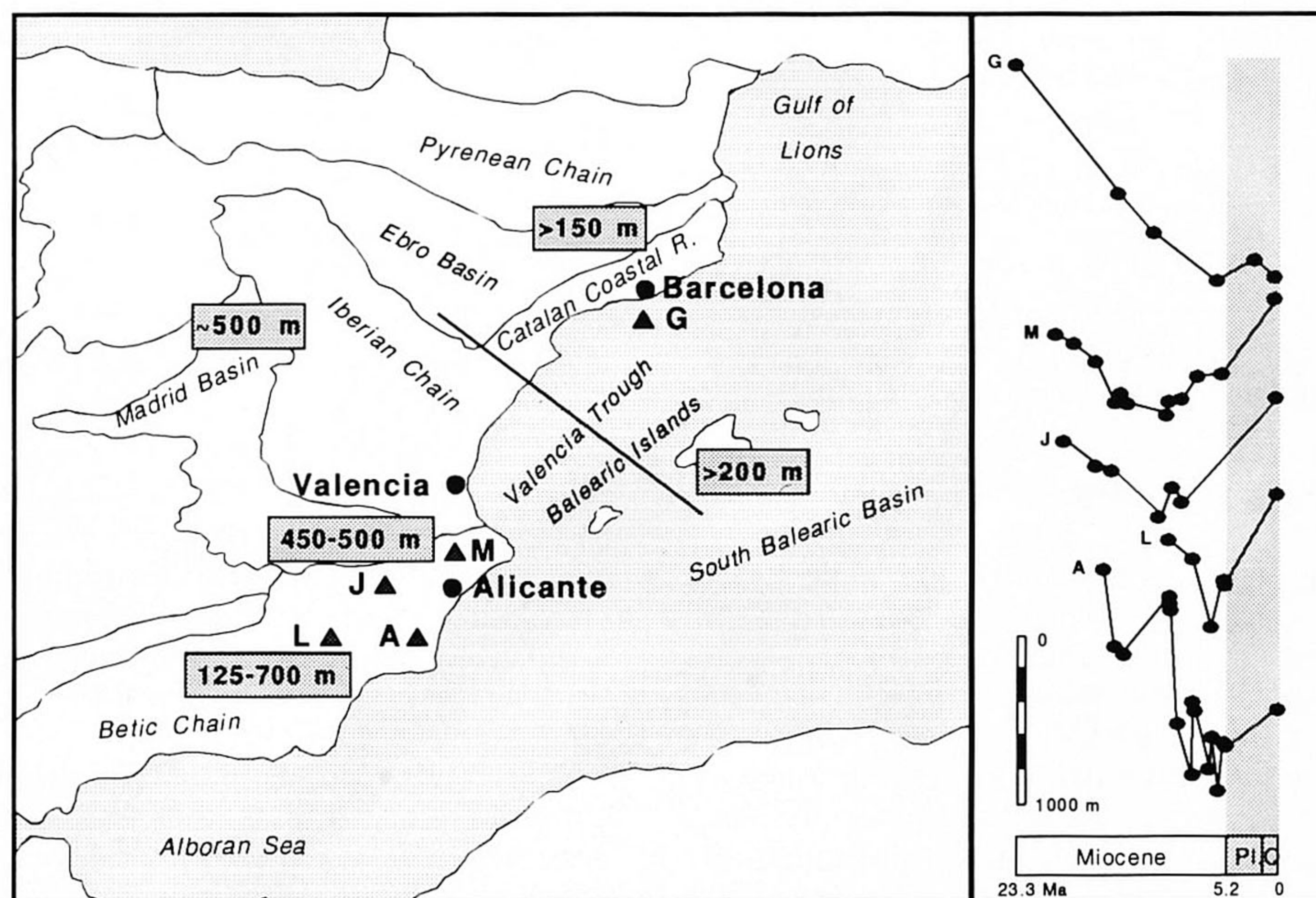


Figure 15 Schematic map of the eastern Iberian margin showing the amount of Pliocene uplift for different basins in the area. The thick solid line marks the location of the profile shown in Figure 16. The triangles mark the sites of the tectonic subsidence curves shown in Panel II. Wells: G = Garraf-1; M = Sierra Mariola (External Betics); J = Prebetic of Jumilla; L = Lorca Basin; and A = Atalya Basin. After Janssen *et al.* (1993)

Table 1 Natural laboratories for integrated studies of basin formation processes by International Lithosphere Program Task Force Origin of Sedimentary Basins. Numbers refer to areas in *Figure 17*

Topic	Basin	Database quality	Prime targets	Key references
Volcanic rifted margins	Mid-Norway Margin (1)	>60 exploration wells seismic database	Effects of volcanism/stress on extensional basin formation	Skogseid and Eldholm (1989) Skogseid <i>et al.</i> (1992a; 1992b) Jensen <i>et al.</i> (1992)
	East Greenland Margin (2)	1993 ODP drilling	Effects of volcanism/stress on extensional basin formation	Larsen and Marcussen (1992) Larsen and Jacobsdottir (1988)
Continental rifting in cratonic lithosphere	North Sea (3)	Thousands of wells, reflection, refraction data, gravity	Effects of stresses on basin formation and inversion, three-dimensional modelling	Ziegler (1990) Ziegler and van Hoorn (1989) Kooi and Cloetingh (1989) Blundell and Gibbs (1990)
	Sverdrup Basin (4)	Exposed rift shoulders	Effects of stress on diapirism, role of volcanism, compressional deformation	Stephenson <i>et al.</i> (1990; 1992) Embry (1989) Stephenson and Ricketts (1990)
	West Siberia Basin (5)	Shallow seismic data and stratigraphic data	Origin of third-order cycles, non-thermal contributions to basin subsidence	Surkov <i>et al.</i> (1982) Milanovsky (1989) Khain <i>et al.</i> (1991)
	Dnieper–Donets Basin (6)	Deep and intermediate seismics, core samples	Origin of third- and fourth-order cycles, rapidly changing tectonic regimes, basin inversion, continental rift origin	Peterson and Clarke (1991) Stephenson <i>et al.</i> (1993) Chekunov <i>et al.</i> (1992)
	Russian Platform (7)	EUROPROBE database	Origin of fourth-order cycles, calibration of sea-level curves	Zonenshain <i>et al.</i> (1990) Lobkovsky <i>et al.</i> (submitted)
	Gulf de Lions (8)	ECORS line	Rift shoulder uplift, rheology	Burrus and Audebert (1991) Kooi <i>et al.</i> (1992)
Extensional basin formation in regimes of overall convergence	Valencia Trough (9)	VALSIS	Necking, effects of stress on basin evolution	Banda and Santenach (1992) Watts and Thorne (1992) Janssen <i>et al.</i> (1993)
	Alboran Sea (10)	Anticipated ODP drilling	Extension mechanisms	Maldonado (1992) Cloetingh <i>et al.</i> (1992)
	Pannonian Basin (11)	Thousands of wells, seismics, gravity and heat flow, Deep Pannonian Geotraverse	Mass and heat transfer, fluid flow	Royden and Horvath (1988) Horvath (1993) Cloetingh <i>et al.</i> (1993b) Posgay <i>et al.</i> (in press) Tari <i>et al.</i> (1992) Ratschbacher <i>et al.</i> (1990)
	Levant Margin (12)	Seismic reflection data	Fault reactivation by collision process	Ben Avraham and Ginzburg (1990) Garfunkel and Derim (1984) Ben Avraham (1978)
Transform margins	Ivory Coast/Ghana Margin (13)	Seismic reflection data	Sheared margin dynamics and structure	Masclé and Blarez (1987)
	South Africa Margin (14) and conjugate margin of Falklands Plateau (15)	Seismic reflection data	Conjugate margin evolution	Scrutton and Dingle (1976) Ben Avraham <i>et al.</i> (1993)
Foreland basin dynamics on young rifted lithosphere	Ebro Basin (16)	ECORS data and extensive outcrop data set	Quantification of interplay thrusting, flexure and eustasy	Puigdefabregas <i>et al.</i> (1992) Zoetemeijer <i>et al.</i> (1990) Chery <i>et al.</i> (1991)
	Aquitaine Basin (17)	ECORS data, well data	Quantification of pre-orogenic subsidence	Desegaulx <i>et al.</i> (1991)
	Betic Foreland (18)	Industry lines, well data	Lateral variation in rheology	van der Beek and Cloetingh (1992)
	Molasse Basin (19) Carpathian Foreland (20)	Subsurface data, hundreds of wells, dense grid of seismic reflection data	Stress and foreland basin evolution; effect of erosion in foreland basin development, models linked to neotectonics	Sinclair <i>et al.</i> (1991) Roure <i>et al.</i> (1993) Royden and Horvath (1988)
Foreland basins on old lithosphere	Alberta Basin (21)	Extensive drilling	Stress and foreland basin evolution	Zoback (1992)
Large-scale compressional basins folding/faulting	Central Australia (22)	Gravity data, seismic reflection data	Dynamics of stress relaxation	Lambeck (1986) Stephenson and Lambeck (1985)
Dynamics of compressional orogens	New Zealand (23)	Excellent exposed	Interaction of erosion processes and lithospheric behaviour in collision zone	Kamp <i>et al.</i> (1989) Willet <i>et al.</i> (1993)
Strike-slip basins	San Andreas fault system (24)	Well known tectonic setting, extensive seismic profiling	Relationship changes in plate motion and basin dynamics	Zoback and Zoback (1991)
	Dead Sea Rift (25)	Extensive data sets, gravity, magnetics, heat flow, seismic reflection and refraction data	Testing of models for formation of transform basins	Ben Avraham <i>et al.</i> (1979) Ben Avraham (1985)

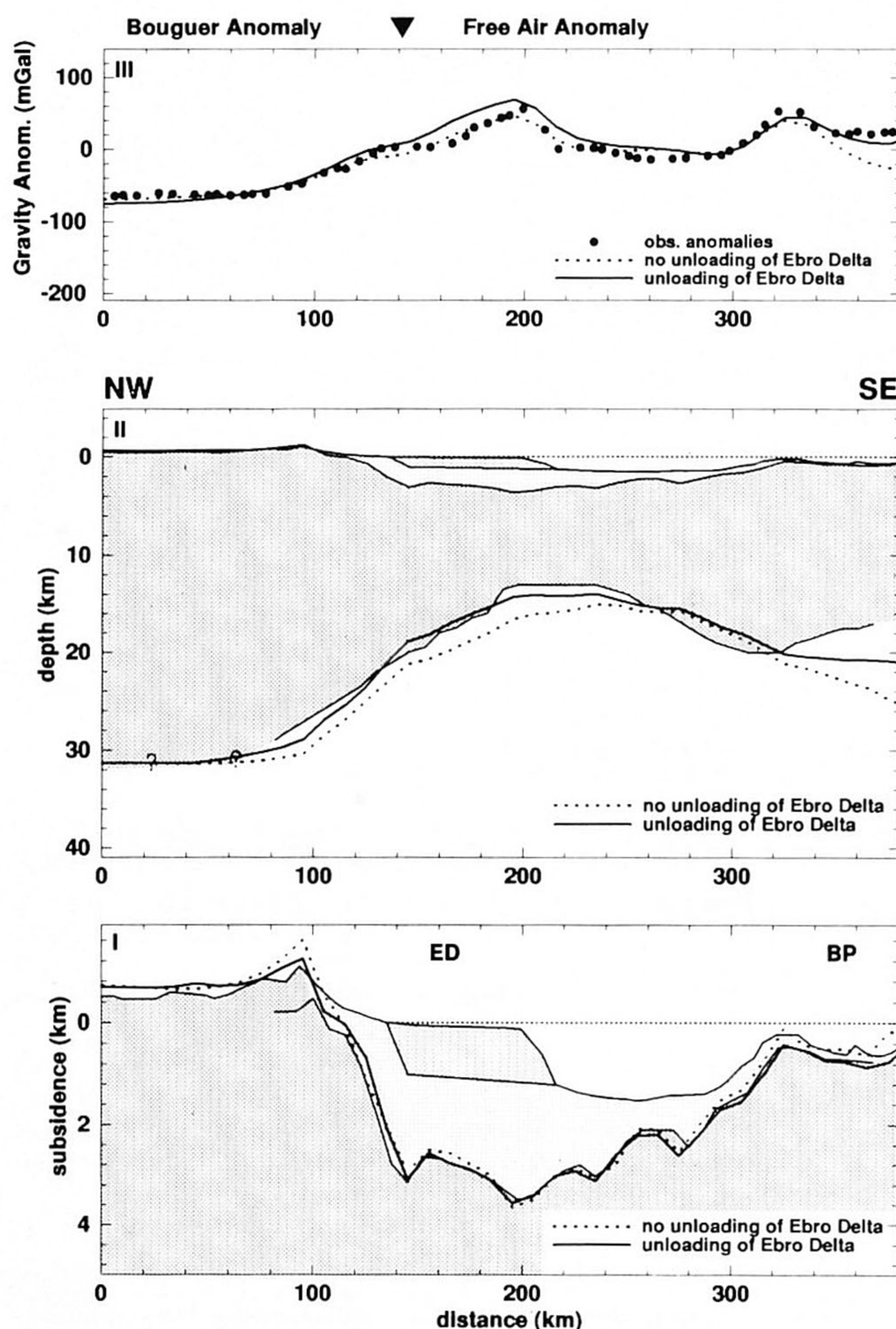


Figure 16 Results of forward modelling of the Valencia Trough adopting a kinematic model incorporating finite strength of the lithosphere during basin formation. Comparison of observed basement configuration and basin configuration predicted by a model with an effective elastic thickness of the lithosphere of 10 km and a depth of necking of 17 km (panel I). Also shown are predicted and observed Moho configuration (panel II) and gravity anomalies (panel III). In case I (solid line) the loading of the Ebro delta has been ignored in the flexural calculations. ED = Ebro Delta; BP = Balaeric Promontory. After Janssen *et al.* (1993)

Trough (Janssen *et al.*, 1993) is the important role of finite strength of the lithosphere and lithospheric necking in creating rift shoulder topography at the basin margins (Figure 15).

Modelling of the dynamics of extension in the Pannonian Basin can elaborate on a substantial and high quality database (e.g. Royden and Horvath, 1988; Horvath, 1993 and other papers on the Pannonian Basin area in Cloetingh *et al.*, 1993b), including the Pannonian Geotraverse (Pogay *et al.*, in press). The observed remarkable variation in structural style shows that the main basin formation mechanisms are fairly complex. Current interpretation suggests that extension was locally very high and rapid uplift of the footwall blocks resulted in the development of metamorphic core complexes (Tari *et al.*, 1992). Such extension occurs by reactivation of Alpine thrusts on low angle normal faults as imaged by seismic sections at

the very western margin of the Pannonian Basin (Figure 13). Rapid uplift and tectonic unroofing of this core complex is also consistent with observations of brittle and ductile deformation by Ratschbacher *et al.* (1990) in the Rechnitz window at the transition zone of the Eastern Alps and the Pannonian Basin. The origin of rapid uplift and associated anomalies in thermal regimes in these extensional terranes forms an important topic for future research. Furthermore, the Pannonian Basin offers the opportunity to develop quantitative models for the interplay between plate boundary forces and extensional collapse on the record of vertical motions.

Research strategy and natural laboratories

A new generation of fully dynamic models at the basin scale is obviously required. Many modelling studies are currently in progress or planned in close interaction with data acquisition focusing on basin history and plate reconstructions, direct observations of the physical state, synthesis of existing geological and geophysical data, in particular quantitative dynamic stratigraphy and regional stratigraphic analyses, petrological and geochemical data, and geophysical data including gravity, magnetics, deep and shallow seismics.

Of major importance in our project is the selection of a number of areas (locations given in Figure 17) for integrated tectonic modelling and basin analysis focusing on both basin fill and the underlying lithosphere. Table 1 summarizes the objectives and pertinent information on background data sets available for these studies.

Products

The prime goal of the Task Force is the development of new concepts on the origin, evolution and resource potential of sedimentary basins. The work of the Task Force aims to facilitate the design of improved predictive tools for integrated basin modelling. The project is carried out over a period of five years with annual workshops for the exchange of progress and preparation of research reports.

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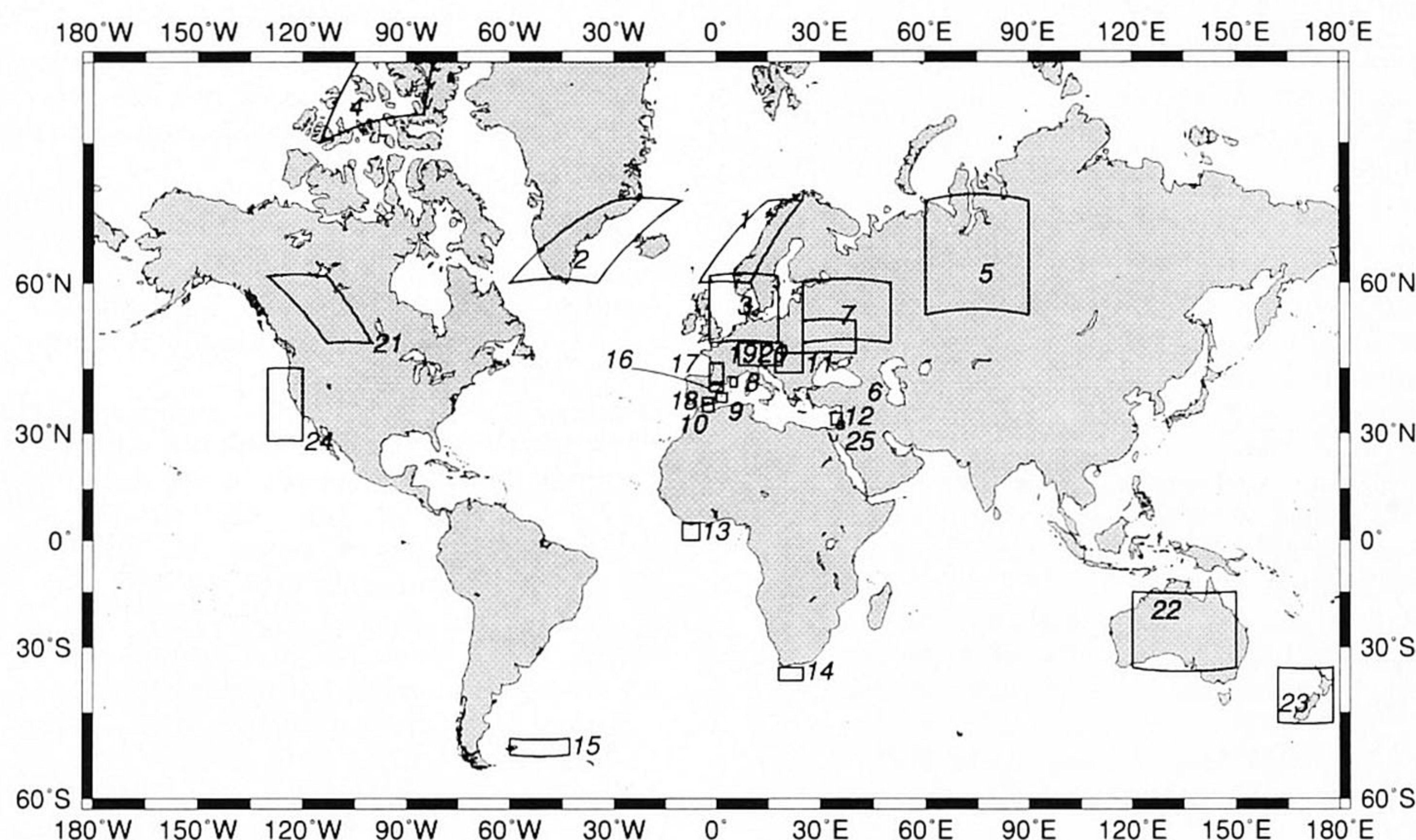


Figure 17 Location map showing sites of the natural laboratories chosen for integrated basin studies by the Task Force (see also Table 1)

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References

- Aigner, T., Brandenburg, A., Van Vliet, A., Doyle, M., Lawrence, D. and Westrich, J. (1990) Stratigraphic modelling of epicontinental basins: two applications *Sedim. Geol.* **69**, 167–190
- Angelier, J. and Colletta, B. (1983) Tension fractures and extensional tectonics *Nature* **301**, 49–51
- Angevine, C. L., Heller, P. L. and Paola, C. L. (1990) Quantitative sedimentary basin modelling *Am. Assoc. Petrol. Geol. Course Note Ser. No. 32*
- Artyushkov, E. V. and Baer, M. A. (1990) Formation of hydrocarbon basins: subsidence without stretching in West Siberia. In: *The Potential of Deep Seismic Profiling for Hydrocarbon Exploration* (Eds B. Pinet and C. Bois), Editions Technip, Paris, 45–61
- Ballentine, C. J., O'Nions, R. K., Oxburgh, E. R., Horvath, F. and Deak, J. (1991) Rare gas constraints on hydrocarbon accumulation, crustal degassing and groundwater flow in the Pannonian basin *Earth Planet. Sci. Lett.* **105**, 229–246
- Banda, E. and Santanach, P. (eds) (1992) *Geology and geophysics of the Valencia trough, Western Mediterranean Tectonophysics* **203**, 1–361
- Bassi, G., Keen, C. E. and Potter, P. (1993) Contrasting styles of rifting: models and examples from the eastern Canadian margin *Tectonics* **12**, 639–655
- Beaumont, C. (1981) Foreland basins *Geophys. J. R. Astron. Soc.* **65**, 291–329
- Beaumont, C. and Tankard, A. J. (Eds) (1987) *Sedimentary Basins and Basin Forming Mechanisms. Can. Soc. Petrol. Geol. Mem.* **12**
- Beekman, F., Bull, J. M., Cloetingh, S. and Strutton, R. A. The relationship between faulting and buckling in the Northern Indian Ocean *Geophys. J. Int.*, submitted
- Ben-Avraham, Z. (1978) The structure and tectonic setting of the Levant continental margin — eastern Mediterranean *Tectonophysics* **46**, 313–331
- Ben-Avraham, Z. (1985) Structural framework of the gulf of Elat (Aqaba) — northern Red Sea *J. Geophys. Res.* **90**, 703–726
- Ben-Avraham, Z. and Ginzburg, A. (1990) Displaced terranes and crustal evolution of the Levant and the eastern Mediterranean *Tectonics* **9**, 613–622
- Ben-Avraham, Z., Almador, G. and Garfunkel, Z. (1979) Sediments and structure of the Gulf of Elat (Aqaba) — northern Red Sea *Sedim. Geol.* **23**, 239–267
- Ben-Avraham, Z., Hartnady, C. J. H. and Malan, J. A. (1993) Agulhas fracture zone tectonics: early opening of the proto-Indian Ocean *Earth Planet. Sci. Lett.* **117**, 43–58

- Bertotti, G., Picotti, V., Bernoulli, D. and Castellarin, A. (1993) From rifting to drifting: tectonic evolution of the south-Alpine upper crust from the Triassic to the Early Cretaceous *Sedim. Geol.* **86**, 53–76
- Beslier, M. O. and Brun, J. P. (1991) Boudinage de la lithosphere et formation des marges passives *C. R. Acad. Sci. Paris* **313**, 951–958
- Blundell, D. J. and Gibbs, A. (Eds) (1990) *Tectonic Evolution of the North Sea Rift*, Oxford University Press, Oxford
- Bois, C. (1993) Initiation and evolution of the Oligo–Miocene rift basins of southwestern Europe: contribution of deep seismic reflection profiling *Tectonophysics*, **226**, 227–252
- Bois, C., Gariel, O. and Pinet, B. (1990) Ecors deep seismic surveys across Paleozoic and Mesozoic basins in France and adjacent areas: a review. In: *The Potential of Deep Seismic Profiling for Hydrocarbon Exploration* (Eds B. Pinet and C. Bois), Editions Technip, Paris, 381–401
- Braun, J. and Beaumont, C. (1989) A physical explanation of the relation between the flank uplifts and the breakup unconformity at rifted continental margins *Geology* **17**, 760–764
- Brun, J.-P. and Tron, V. (1993) Development of the North Viking graben: inferences from laboratory modelling *Sedim. Geol.* **86**, 31–51
- Buck, R. (1991) Modes of continental lithospheric extension *J. Geophys. Res.* **96**, 20 161–20 178
- Burg, J.-P., Mainprice, D. and Petit, J.-P. (Eds) (1992) Mechanical instabilities in rocks and tectonics *J. Struct. Geol.* **14**, 893–1109
- Burrus, J. and Audebert, F. (1991) Thermal and compaction processes in a young rifted basin containing evaporites: Gulf of Lions, France *Am. Assoc. Petrol. Geol. Bull.* **74**, 1420–1440
- Carrigan, C. R., King, G. C. P., Barr, G. E. and Bixler, N. E. (1991) Potential for water-table excursions induced by seismic events at Yucca Mountain, Nevada *Geology* **19**, 1157–1160
- Carter, N. L. and Tsenn, M. C. (1987) Flow properties of continental lithosphere *Tectonophysics* **136**, 27–63
- Cartwright, J. A. (1994) Episodic basin-wide hydrofracturing of overpressured Early Cenozoic mudrock sequences in the North Sea Basin *Mar. Petrol. Geol.* **11**, 587–607
- Chekunov, A. V., Gavrish, V. K., Kutas, R. I. and Ryabchum, L. I. (1992) Dnieper-Donets paleorift *Tectonophysics* **208**, 257–272
- Chery, J., Vilotte, J. P. and Daignieres, M. (1991) Thermo-mechanical evolution of a thinned continental lithosphere under compression: implications for the Pyrenees *J. Geophys. Res.* **96**, 4385–4412
- Cloetingh, S. and Kooi, H. (1992) Tectonic stress and dynamical aspects of rifted sedimentary basins *Tectonophysics* **215**, 167–185
- Cloetingh, S., McQueen, H. and Lambreck, K. (1985) On a tectonic mechanism for regional sealevel variations *Earth Planet. Sci. Lett.* **75**, 157–164
- Cloetingh, S., Kooi, H. and Groenewoud, W. (1989) *Intraplate Stresses and Sedimentary Basin Evolution*. *Am. Geophys. Union Geophys. Monogr. No. 48*, 1–16
- Cloetingh, S., Van der Beek, P. A., Van Rees, D., Roep, T. B., Biermann, C. and Stephenson, R. A. (1992) Flexural interaction and the dynamics of Neogene extensional basin formation in the Alboran-Betic region *Geo-Mar. Lett.* **12**, 66–75
- Cloetingh, S., Sassi, W., Horvath, F. and Puigdefabregas, C. (Eds) (1993a) Basin analysis and dynamics of sedimentary basin evolution *Sedim. Geol.* **86**, 201 pp
- Cloetingh, S., Sassi, W. and Horvath, F. (Eds) (1993b) The origin of sedimentary basins: inferences from quantitative modelling and basin analysis *Tectonophysics*, **226**, 518 pp
- Cloetingh, S., Eldholm, O., Sassi, W., Larsen, B. T. and Gabrielsen, R. (Eds) Dynamics of extensional basin formation and inversion *Tectonophysics*, in press
- Cobbold, P. R., Davy, P., Gapais, D., Rosello, E. A., Sadybakasov, E., Thomas, J. C., Tondji Biyo, J. J. and de Urreizatieta, M. (1993) Sedimentary basins and crustal thickening *Sedim. Geol.* **86**, 77–89
- Colletta, B., Letouzey, J., Pinedo, R., Ballard, J.-F. and Bale, P. (1991) Computerized X-ray tomography analysis of sandbox models: examples of thin-skinned thrust systems *Geology* **19**, 1063–1067
- Csontos, L., Tari, G., Bergerat, F. and Fodor, L. (1991) Evolution of stress fields in the Carpatho–Pannonian area during the Neogene *Tectonophysics* **199**, 73–91
- Dahlstrom, C. D. A. (1969) Balanced cross sections *Can. J. Earth Sci.* **6**, 743–757
- Dahlstrom, C. D. A. (1970) Structural geology in the eastern margin of the Canadian Rocky Mountains *Bull. Can. Soc. Petrol. Geol.* **18**, 332–406
- Daudré, B. and Cloetingh, S. Numerical modelling of salt diapirism: influence of the tectonic regime *Tectonophysics*, in press
- Desegaulx, P., Kooi, H. and Cloetingh, S. (1991) Consequences of foreland basin development on thinned continental lithosphere: application to the Aquitaine Basin, (SW France) *Earth Planet. Sci. Lett.* **106**, 116–132
- Dunbar, J. A. and Sawyer, D. S. (1989) How preexisting weakness zones control the style of continental breakup *J. Geophys. Res.* **94**, 7278–7292
- Dupin, J. M., Sassi, W. and Angelier, J. (1993) Homogeneous stress hypothesis and actual fault slip: a distinct element analysis *J. Struct. Geol.* **15**, 1033–1043
- Ebinger, C. J., Karner, G. D. and Weissel, J. K. (1991) Mechanical strength of extended continental lithosphere: constraints from the western rift system, Africa *Tectonics* **10**, 1239–1256
- Eldholm, O., Thiede, J. et al. (eds) (1989) *Proc. ODP* **104**, 1141 pp
- Embry A. F. (1989) A tectonic origin for third-order depositional sequences in extensional basins — implications for basin modelling. In: *Quantitative Dynamic Stratigraphy* (Ed. T. A. Cross), Prentice Hall, New York, 491–501
- Flemming, P. B. and Jordan, T. E. (1989) A synthetic stratigraphic model of foreland basin development *J. Geophys. Res.* **94**, 3851–3866
- Garfunkel, Z. (1988) Relation between continental rifting and uplifting: evidence from the Suez rift and northern Red Sea *Tectonophysics* **150**, 33–49
- Garfunkel, Z. and Derin, B. (1984) Permian–early Mesozoic tectonism and continental margin formation in Israel and its implications for the history of the eastern Mediterranean. In: *The Geological Evolution of the Eastern Mediterranean* (Eds J. E. Dixon and H. F. Robertson), 187–202
- Gibbs, A. D. (1983) Balanced cross-section constructions from seismic sections in areas of extensional tectonics *J. Struct. Geol.* **5**, 152–160
- Gibbs, A. D. (1987) Development of extensional and mixed mode sedimentary basins. In: *Continental Extensional Tectonics* (Eds M. P. Coward, J. F. Dewey and P. L. Hancock), *Spec. Publ. Geol. Soc. London No. 28*, 19–33
- Gibbs, A. D. (1989) Structural styles in basin formation. In: *Extensional Tectonics and Stratigraphy of the North Atlantic Margins* (Eds A. J. Tankard and H. R. Balkwill), *Am. Assoc. Petrol. Geol. Mem. No. 46*, 81–93
- Gillespie, P. A., Howard, C. B., Walsh, J. J. and Watterson, J. (1993) Measurement and characterisations of spatial distribution of fractures *Tectonophysics* **223**, 113–141
- Hinz, K., Fritsch, J., Kempter, E. H. K., Manaf Mohammad, A., Meyer, J., Mohamed, D., Vosberg, H., Weber, J. and Benavidez, J. (1989) Thrust tectonics along the northwestern continental margin of Sabah/Borneo *Geol. Rundsch.* **78**, 705–730
- Horvath, F. (1993) Towards a kinematic model for the formation of the Pannonian basin *Tectonophysics* **226**, 333–357
- Hyndman R. D. (1988) Dipping seismic reflectors, electrically conductive zones and trapped water in the crust over a subducting plate *J. Geophys. Res.* **93**, 13 391–13 405
- Jackson, J. A. (1980) Reactivation of basement faults and crustal shortening in orogenic belts *Nature* **283**, 343–346
- Jamieson, R. A. and Beaumont, C. (1989) Deformation and metamorphism in convergent orogens: a model for uplift and exhumation of metamorphic terrains. In: *Evolution of Metamorphic Belts* (Eds J. S. Daly, R. A. Cliff and B. W. D. Yardley), *Spec. Publ. Geol. Soc. London No. 43*, 117–129
- Janssen, M., Thorne, M., Cloetingh, S. and Banda, E. (1993) Pliocene uplift of the eastern Iberian margin: inferences from quantitative modelling of the Valencia Trough *Earth Planet. Sci. Lett.* **119**, 585–597
- Jensen, L. N., Riis, F. and Boyd, R. (Eds) (1992) Post-Cretaceous uplift and sedimentation along the western Fennoscandian shield *Norsk Geol. Tidssk.* **72**, 221–338

- Jenyon, M. K. (1986) *Salt Tectonics*, Elsevier Applied Science, New York, 191 pp
- Kamp, P. J., Green, P. F. and White, S. H. (1989) Fission track analysis reveals character of collisional tectonics in New Zealand *Tectonics* **8**, 169–195
- Keen, C. E., Boutilier, B., De Voogd, B., Mudford, B. and Enachescu, M. E. (1987) Crustal geometry and extension models for the Grand Banks, eastern Canada: constraints from deep seismic reflection data. In: *Sedimentary Basins and Basin Forming Mechanisms* (Eds C. Beaumont and A. J. Tankard), *Can. Soc. Petrol. Geol. Mem. No. 12*, 101–116
- Kenyon, P. M. and Turcotte, D. L. (1985) Morphology of a delta prograding by bulk sediment transport *Geol. Soc. Am. Bull.* **96**, 1457–1465
- Khain, V. E., Sokolov, B. A., Kleshchev, K. A. and Shein, V. S. (1991) Tectonic and geodynamic setting of oil and gas basins of the Soviet Union *Am. Assoc. Petrol. Geol. Bull.* **75**, 313–325
- King, G. C. P., Stein, R. S. and Rundle, J. B. (1988) The growth of geological structures by repeated earthquakes, 1. Conceptual framework *J. Geophys. Res.* **93**, 13307–13318
- Klemperer, S. and Hobbs, R. (1991) *The BIRPS Atlas — Deep Seismic Reflection Profiles Around the British Isles*, Cambridge University Press, Cambridge
- Klemperer, S. L. and Matthews, D. H. (1987) Iapetus suture located beneath the North Sea by BIRPS deep seismic reflection profiling *Geology* **15**, 195–198
- Klemperer, S. L., Hauge, T. A., Hauser, E. C., Oliver, J. E. and Potter, C. J. (1986) The Moho in the Northern Basin and range province, Nevada, along the COCORP 40 deg. Seismic reflection transect *Geol. Soc. Am. Bull.* **97**, 603–618
- Knipe, R. (1985) Footwall geometry and the rheology of thrust sheets *J. Struct. Geol.* **71**, 1–10
- Kooi, H. and Beaumont, C. (1994) Escarpment evolution on high-elevation rifted margins; insights derived from a surface processes model that combines diffusion, advection and reaction *J. Geophys. Res.* **99**, 12191–12209
- Kooi, H. and Cloetingh, S. (1989) Some consequences of late-stage compression for extensional models of basin evolution *Geol. Rundsch.* **78**, 183–195
- Kooi, H. and Cloetingh, S. (1992) Lithospheric necking and regional isostasy at extensional basins 2. Stress-induced vertical motions and relative sea level changes *J. Geophys. Res.* **97**, 17573–17591
- Kooi, H., Cloetingh, S. and Burrus, J. (1992) Lithospheric necking and regional isostasy at extensional basins: part 1, subsidence and gravity modelling with an application to the Gulf de Lions (SE France) *J. Geophys. Res.* **97**, 17553–17571
- Kusznir, N. J. and Ziegler, P. A. (1992) The mechanics of continental extension and sedimentary basin formation: a simple-shear/pure-shear flexural cantilever model *Tectonophysics* **215**, 117–131
- Kusznir, N. J., Marsden, G. and Egan S. S. (1991) A flexural-cantilever simple-shear/pure-shear model of continental lithosphere extension: application to the Jeanne d'Arc Basin, Grand Banks and Viking Graben, North Sea. In: *The Geometry of Normal Faults* (Eds A. M. Roberts, G. Yielding and B. Freeman), *Spec. Publ. Geol. Soc. No. 56*, 41–60
- Lambeck, K. (1986) Crustal structure and evolution of the central Australian basins. In: *Nature of the Lower Crust* (Eds J. B. Dawson, D. A. Carswell, J. Hall and K. H. Wedepohl), *Spec. Publ. Geol. Soc. London No. 24*, 133–145
- Larsen, H. C. and Jacobsdottir, S. (1988) Distribution, crustal properties and significance of seawards-dipping sub-basement reflectors off E. Greenland. In: *Early Tertiary Volcanics and the Opening of the NE Atlantic* (Eds A. C. Morton and L. M. Parson), *Spec. Publ. Geol. Soc. London No. 39*, 95–114
- Larsen, H. C. and Marcussen, C. (1992) Sill intrusions, flood-basalt emplacement and deep crustal structure of the Scoresby Sund region East Greenland. In: *Magmatism and the Causes of Continental Break-up* (Eds B. C. Storey, T. Alabaster and R. J. Pankhurst), *Spec. Publ. Geol. London No. 68*, 365–386
- Last, N. (1988) Deformation of a sedimentary overburden on a slowly creeping substratum. In: *Numerical Methods in Geomechanics (Innsbruck 1988)* (Ed. G. Swoboda), Balkema, Rotterdam, 577–585
- LePichon, X. and Chamot-Rooke, C. (1991) Extension of continental crust. In: *Controversies in Modern Geology*, Academic Press, New York, 313–338
- Leroy, Y. M. and Molinari, A. (1993) Spatial patterns and size effects in shear zones: a hyperelastic model *J. Mech. Phys. Solids* **41**, 631–664
- Letouzey J. (1986) Cenozoic paleo-stress pattern in the Alpine foreland and structural interpretation in a platform basin *Tectonophysics* **132**, 215–231
- Letouzey J. (1990) Fault reactivation, inversion and fold-thrust belt. In: *Petroleum and Tectonics in Mobile Belts* (Ed. J. Letouzey), Editions Technip, Paris, 101–128
- Lie, J. E. and Husebye, E. S. (1994) Simple-shear deformation of the Skagerrak lithosphere during the formation of the Oslo rift *Tectonophysics* **232**, 133–141
- Lobkovsky, L., Cloetingh, S., Nikishin, A., Milanovsky, E. E. and Lankreijer, A. Extensional basins of the former U.S.S.R. — structure and basin formation mechanisms *Tectonophysics*, submitted
- Lohner, R. (1989) Adaptive remeshing for transient problems *Comput. Meth. Appl. Mech. Engin.* **75**, 195–214
- Ma, X. Q. and Kusznir, N. J. 3D surface displacement and strain fields for faults and fault arrays in a layered elastic halfspace, in preparation
- Main, I. G., Meredith, P. J., Simmonds, P. R. and Jones, C. (1990) Influence of fractal flow distributions on rock deformation in the brittle field. In: *Deformation Mechanisms, Rheology and Tectonics* (Eds R. G. Knipe and E. H. Rutter), *Spec. Publ. Geol. Soc. London No. 54*, 71–79
- Maldonado, A. (Ed.) (1992) *Structure and Evolution of the Alboran Sea. Special Issue, Geo-mar. Lett.* **12**, 61–186
- Mandl, G. (1988) *Mechanics of Tectonic Faulting*, Elsevier, Amsterdam, 407 pp
- Masce, J. and Blarez, E. (1987) Evidence for transform margin evolution from the Ivory Coast — Ghana continental margin *Nature* **236**, 378–381
- McClay, K. R. and Ellis, P. G. (1987) Analogue models of extensional fault geometries. In: *Continental Extensional Tectonics* (Eds J. Y. P. Coward, J. F. Dewey and P. L. Hancock), *Spec. Publ. Geol. Soc. London No. 28*, 109–125
- McKenzie, D. P. (1978) Some remarks on the development of sedimentary basins *Earth Planet. Sci. Lett.* **40**, 25–32
- Melosh, J. (1990) Mechanical basis for low-angle normal faulting in the Basin and Range province *Nature* **343**, 331–325
- Milanovsky, E. E. (1989) *Geology of the USSR*, Moscow University Press, Moscow, 360 pp
- Moretti, I., Triboulet S. and Endignoux L. (1990) Some remarks on the geometrical modeling of geological deformations. In: *Petroleum and Tectonics in Mobile Belts* (Ed. J. Letouzey), Editions Technip, Paris, 155–162
- Mueller, B., Zoback, M. L., Fuchs, F., Mastin, L., Gregersen, S., Pavoni, N., Stephansson, O. and Lunggren, C. (1992) Regional patterns of stress in Europe *J. Geophys. Res.* **97**, 11783–11803
- Nieuwland, D. A. and Walters, J. V. (1993) Geomechanics of the South Furious Field: an integrated approach towards solving complex structural problems, including analogue and finite-element modelling *Tectonophysics* **226**, 143–166
- Nunns, A. G. (1991) Structural restoration of seismic and geologic sections in extensional regimes *Am. Assoc. Petrol. Geol. Bull.* **75**, 278–297
- Pedersen, T. and Skogseid, J. (1989) Vøring Plateau volcanic margin: extension melting and uplift *Proc. ODP*, **104**, 985–991
- Peper, T., Beekman, F. and Cloetingh, S. (1992) Consequences of thrusting and intraplate stress fluctuations for vertical motions in foreland basins and peripheral areas *Geophys. J. Int.* **111**, 104–126
- Peper, T., Van Balen, R. T. and Cloetingh, S. Numerical models of eustatic and tectonic control on foreland basin stratigraphy. In: *Stratigraphic Development in Foreland Basins* (Eds S. L. Dorobek and G. M. Ross), *Spec. Publ. Soc. Econ. Paleontol. Mineral.*, in press
- Peterson, J. A. and Clarke, J. W. (1991) *Geology and Hydrocarbon Habitat of the West Siberian Basin*. *Am. Assoc. Petrol. Geol. Stud. Geol. No. 32*, 96 pp

- Philip, H. (1987) Plio-Quaternary evolution of the stress field in Mediterranean zones of subduction and collision, *Ann. Geophys.* **5b**, 301–320
- Pinet, B. and Bois, C. (Eds) (1990) The potential of deep seismic profiling for hydrocarbon exploration *Proc. 5th IFP Expl. Prod. Res. Conf. Arles, France*, Editions Technip, Paris, 474 pp
- Pitman, W. C. and Andrews, J. A. (1985) Subsidence and thermal history of small pull-apart basins *Spec. Publ. Soc. Econ. Paleont. Miner. No. 37*, 45–49
- Posgay, K., Hegedus, E. and Timar, Z. Reflection images of wrench faulting and rifting events in the lithosphere-asthenosphere system below the Pannonian Basin *Tectonophysics* in press
- Puigdefabregas, C., Munoz, J. A. and Verges J. (1992) Thrusting and foreland basin evolution in the Southern Pyrenees. In: *Thrust Tectonics* (Ed. K. R. McClay), Chapman and Hall, London, 247–254
- Quinlan, G. M. and Beaumont, C. (1984) Appalachian thrusting, lithospheric flexure and the Paleozoic stratigraphy of the Eastern Interior of North America *Can. J. Earth. Sci.* **21**, 973–996
- Quinlan, G., Walsh, J., Skogseid, J., Sassi, W., Cloetingh, S., Lobkovsky, L., Bois, C., Stel, H. and Banda, E. (1993) Relationship between deeper lithospheric processes and near-surface tectonics of sedimentary basins *Tectonophysics* **226**, 217–225
- Ratschbacher, L., Behrmann, J. H. and Pahr, A. (1990) Penninic windows at the eastern end of the Alps and their relation to the intra-Carpathian basins *Tectonophysics* **172**, 91–105
- Roberts, A. and Yielding, G. (1992) Deformation around basin-margin faults in the North Sea/mid-Norway rift. In: *The Geometry of Normal Faults* (Eds A. M. Roberts, G. Yielding and B. Freeman), *Spec. Publ. Geol. Soc. London No. 56*
- Robinson, A. G., Coleman, M. L. and Gluyas, J. G. (1993) The age and cause of illite cement growth, Village Fields area, southern North Sea: evidence from K–Ar ages and $^{18}\text{O}/^{16}\text{O}$ ratios *Am. Assoc. Petrol. Geol. Bull.* **77**, 68–80
- Roure, F., Roca, E. and Sassi, W. (1993) The Neogene evolution of the southern Carpathian flysch units (Poland, Ukraine and Romania: kinematics of a foreland-fold-and-thrust belt system *Sedim. Geol.* **86**, 177–201
- Royden, L. and Horvath, F. (Eds) (1989) *Structure and Evolution of the Pannonian Basin*. *Am. Assoc. Petrol. Geol. Mem. No. 45*
- Royden, L. and Keen, C. E. (1980) Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves *Earth Planet. Sci. Lett.* **51**, 343–361
- Sassi, W., Colletta, B., Bale, P. and Paquereau, T. (1993) Modelling of structural complexity in sedimentary basins: the role of pre-existing faults in thrust tectonics *Tectonophysics* **226**, 97–112
- Schlager, W. (1993) Accommodation and supply — a dual control on stratigraphic sequences *Sedim. Geol.* **86**, 111–136
- Schneider, F., Burrus, J. and Wolf, S. (1993) Modelling overpressures by effective-stress/porosity relationships in low permeability rocks: empirical artifacts or physical reality? In: *Basin Modelling: Advances and Applications* (Ed. A. G. Doré), Elsevier, Amsterdam, 333–341
- Scholz, C. H. and Cowie, P. A. (1990) Determination of total strain from faulting using slip measurements *Nature* **346**, 837–839
- Schwerdtner, W. M. and Osadetz, K. (1983) Evaporite diapirism in the Sverdrup Basin: New insights and unsolved problems *Bull. Can. Petrol. Geol.* **31**, 27–36
- Scrutton, R. A. and Dingle, R. V. (1976) Observation on the processes of sedimentary basin formation at the margins of margins of southern Africa *Tectonophysics* **36**, 143–156
- Sibson, R. H. (1981) Fluid flow accompanying faulting: field evidence and models. In: *Earthquake Prediction: an International Review* (Eds D. W. Simpson and P. G. Richards), *Maurice Ewing Series*, Vol. 4, American Geophysical Union, Colorado, 593–603
- Sibson, R. H. (1990) Conditions for fault-valve behaviour. In: *Deformation Mechanisms, Rheology and Tectonics* (Eds R. J. Knipe and E. H. Rutter), *Spec. Publ. Geol. Soc. London No. 54*, 15–28
- Sinclair, H. D., Coakley, B. J., Allen, P. A. and Watts, A. B. (1991) Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: an example from the central Alps, Switzerland *Tectonics* **10**, 599–620
- Skogseid, J. and Eldholm, O. (1987) Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge *J. Geophys. Res.* **92**, 11 471–11 491
- Skogseid, J. and Eldholm, O. (1989) Voring plateau continental margin; seismic interpretation, stratigraphy and vertical movements *Proc. ODP* **104**, 993–1030
- Skogseid, J., Pedersen, T., Eldholm, O. and Larsen, B. T. (1992a) Tectonism and magmatism during NE Atlantic continental breakup: the Voring margin. In: *Magmatism and the Causes of Continental Breakup* (Eds B. C. Storey, T. Alabaster and R. J. Planhurst), *Spec. Publ. Geol. Soc. London No. 68*, 305–320
- Skogseid, J., Pedersen, T. and Larsen, V. B. (1992b) Voring Basin: subsidence and tectonic evolution. In: *Structural and Tectonic Modelling and its Application to Petroleum Geology* (Eds R. M. Larsen et al.), *Spec. Publ. Norw. Petrol. Soc. No. 1*, 55–82
- Sleep, N. H. (1971) Thermal effects of the formation of Atlantic margins by continental margins by continental break-up *Geophys. J. R. Astron. Soc.* **24**, 325–350
- Stel, H., Cloetingh, S., Heeremans, M. and Van der Beek, P. A. (1993) The kinematics of anorogenic basement tectonics and the origin of sedimentary basins *Tectonophysics* **226**, 285–299
- Stephenson, R. A. and Lambeck, K. (1985) Isostatic response of the lithosphere with in-plane stress: application to central Australia *J. Geophys. Res.* **90**, 8581–8588
- Stephenson, R. A. and EUROPROBE team (1993) Continental rift development in Precambrian and Phanerozoic Europe: EUROPROBE and the Dnieper–Donets Rift and Polish Trough Basins *Sedim. Geol.* **86**, 159–175
- Stephenson, R. A. and Ricketts, B. D. (1990) Bouguer gravity anomalies and speculations on the regional crustal structure of the Eurekan Orogen, Arctic Canada *Mar. Geol.* **93**, 401–420
- Stephenson, R. A., Van Berkel, J. T. and Cloetingh, S. (1992) Relation between salt diapirism and tectonic history of the Sverdrup Basin, Arctic Canada *Can. J. Earth. Sci.* **29**, 2695–2705
- Stephenson, R. A., Ricketts, B., Cloetingh, S. and Beekman, F. (1990) Lithosphere folds in the Eurekan orogen, Arctic Canada? *Geology* **18**, 603–606
- Stockmal, G. S., Beaumont, C. and Boutelier, R. (1986) Geodynamic models of convergent margin tectonics: the transition from rifted margin to overthrust belt and the consequences for foreland basin development *Am. Assoc. Petrol. Geol. Bull.* **70**, 181–390
- Sundvoll, B., Larsen, B. T. and Wandaas, B. (1992) Early magmatic phase in the Oslo Rift and its related stress regime *Tectonophysics* **208**, 37–54
- Suppe, J. (1983) Geometry and kinematics of fault bend folding *Am. J. Sci.* **283**, 684–722
- Surkov, V. S., Trofimuk, A. A., Zhero, O. G., Kontorovich, A. E. and Smirnov, L. V. (1982) Triassic Rift system of the West Siberian plate, its influence on structure and hydrocarbons of the Mesozoic–Cenozoic platform cover [in Russian] *Geol. Geofiz.* **8**, 3–15
- Tankard, A. J. and Balkwill, R. (Eds) (1989) Extensional tectonics and stratigraphy of the North Atlantic Margins *Am. Assoc. Petrol. Geol. Mem. No. 46*, 641 pp
- Tari, G., Horvath, F. and Rumpler, J. (1992) Styles of extension in the Pannonian Basin *Tectonophysics* **208**, 203–219
- Ten Brink, U.S. and Ben-Avraham, Z. (1989) The anatomy of pull-apart basin: seismic reflection observations of the Dead Sea basin *Tectonophysics* **8**, 351–362
- Touret, J. L. R. (1992) CO₂ transfer between the upper mantle and the atmosphere: temporary storage in the lower continental crust *Terra Nova* **4**, 87–98
- Van Balen, R. T. and Cloetingh, S. (1993) Intraplate stresses and fluid flow in extensional basins. In: *Diagenesis and Basin Development* (Eds A. Horbury and A. Robinson), *Am. Assoc. Petrol. Geol. Stud. Geol.* **36**, 87–98
- Van Balen, R. T., Cloetingh, S. and Reemst, P. (1994) Tectonic control of the sedimentary record and shear-induced fluid flow: constraints from basin modelling. In: *Geofluids:*

- Origin, Migration and Evolution of Fluids in Sedimentary Basins (Ed. J. Parnell), *Spec. Publ. Geol. Soc. London* No. 78, 9–26
- Van der Beek, P. A. and Cloetingh S. (1992) Lithospheric flexure and tectonic evolution of the Betic Cordilleras (SE Spain) *Tectonophysics* **203**, 325–344
- Van der Beek, P. A., Cloetingh, S. and Andriessen, P. A. M. (1994) Extensional basin formation mechanisms and vertical motions at rift flanks: constraints from tectonic modelling and fission track analysis *Earth Planet. Sci. Lett.* **121**, 417–433
- Van Wees, J. D. and Cloetingh, S. (1991) Finite element models for basin extension and inversion. In: *Analysis and Modelling of Faulting* (Ed. F. Bergerat), *Special Meeting of the Geological Society of France, Paris, 8–9 December 1991, Abstract Volume*, 72
- Van Wees, J. D. and Cloetingh, S. (1994) A finite difference technique to incorporate spatial variations in rigidity and planar faults into 3D models for lithospheric flexure *Geophys. J. Int.* **117**, 179–195
- Vendeville, B. and Cobbold P. (1987) Glissement gravitaires synsedimentaires et failles normales listriques: modèles experimentaux *C.R.A.S.* **305**, 1313–1318
- Vilotte, J.P., Melosh, J., Sassi, W. and Ranalli, G. (1993) Lithosphere rheology and sedimentary basins *Tectonophysics* **226**, 89–95
- Walsh, J. J. and Waterson, J. (1988) Analysis of the relationship between the displacements and dimensions of faults *J. Struct. Geol.* **9**, 239–247
- Walsh, J., Waterson, J. and Yielding, G. (1991) The importance of small scale faulting in regional extension *Nature* **351**, 391–393
- Warner, M. and McGeary, S. (1987) Seismic reflection coefficients from mantle fault zones *Geophys. J. R. Astron. Soc.* **89**, 223–230
- Watts, A. B. (1989) Lithospheric flexure due to prograding sediment loads: implications for the origin of offlap/onlap patterns in sedimentary basins *Basin Res.* **2**, 133–144
- Watts, A. B. and Thorne, M. (1992) Crustal structure and the mechanical properties of extended continental lithosphere in the Valencia Trough (western Mediterranean) *J. Geol. Soc. London* **149**, 813–827
- Weissel, J. K. and Karner, G. D. (1989) Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension *J. Geophys. Res.* **94**, 13919–13950
- Wernicke, B. (1985) Uniform sense normal simple shear of the continental lithosphere *Can. J. Earth Sci.* **22**, 108–125
- Wernicke, B. and Burchfield, B. C. (1982) Modes of extensional tectonics *J. Struct. Geol.* **4**, 105–115
- Westaway, R. and Kusznir, N. (1993) Fault and bed 'rotation' during continental extension: block rotation or vertical shear? *J. Struct. Geol.* **15**, 753–770
- White, R. S. (1992) Crustal structure and magmatism of north Atlantic continental margins *J. Geol. Soc. London* **149**, 841–854
- Willett, S., Beaumont, C. and Fullsack, P. (1993) Mechanical model for the tectonics of doubly vergent compressional orogens *Geology* **21**, 371–374
- Wilson, M. (1993) Magmatism and the geodynamics of basin formation *Sedim. Geol.* **86**, 5–29
- Wortel, M. J. R. and Spakman, W. (1992) Structure and dynamics of subducted lithosphere in the Mediterranean region *Proc. Kon. Ned. Akad. Wetensch.* **95**, 325–347
- Ziegler, P. A. (1987) Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland — a geodynamic model *Tectonophysics* **137**, 389–420
- Ziegler, P. A. (1988) *Evolution of the Arctic North Atlantic and Western Tethys*. *Am. Assoc. Petrol. Geol. Mem. No. 43*, 198 pp
- Ziegler, P. A. (1990) *Geological Atlas of Western and Central Europe*, Shell Internationale, The Hague, 239 pp
- Ziegler, P. A. (Ed.) (1992) *Geodynamics of Rifting*. *Tectonophysics* **215**, 1–253
- Ziegler, P. A. and Van Hoorn, B. (1989) *Evolution of the North Sea Rift System*. *Am. Assoc. Petrol. Geol. Mem. No. 46*, 471–500
- Zoback, M. L. (1992) First and second order patterns of stress in the lithosphere *J. Geophys. Res.* **97**, 11 703–11 728
- Zoback, M. L. and Zoback, M. D. (1989) Tectonic stress field of the continental United States. In: *Geophysical Framework of the Continental United States* (Eds L. Pakiser and W. Mooney), *Geol. Soc. Am. Mem. No. 172*, 523–539
- Zoback, M. D. and Zoback, M. L. (1991) Tectonic stress field of North America and relative plate motions. In: *Neotectonics of North America* (Eds D. B. Slemmons, E. R. Engdahl, M. D. Zoback and D. D. Blackwell), *Geol. Soc. Am. Decade Map*, Vol. 1, 339–366
- Zoback, M. D., Stephenson, R. A., Cloetingh, S., Larsen, B. T., Van Hoorn, B., Robinson, A., Horvath, F., Puigdefabregas, C. and Ben-Avraham, Z. (1993) Stresses in the lithosphere and sedimentary basin formation *Tectonophysics* **226**, 1–13
- Zoetemeijer, R. and Sassi, W. (1992) 2-D reconstruction of thrust evolution using the fault-bend fold method. In: *Thrust Tectonics* (Ed. K. R. McClay), Chapman and Hall, London, 133–140
- Zoetemeijer, R., Desegaulx, P., Cloetingh, S., Roure, F. and Morreti, I. (1990) Lithospheric dynamics and tectonic-stratigraphic evolution of the Ebro basin *J. Geophys. Res.* **95**, 2701–2711
- Zoetemeijer, R., Sassi, W., Roure, F. and Cloetingh, S. (1992) Stratigraphic and kinematic modelling of thrust evolution: Northern Apennines, Italy *Geology* **20**, 1035–1038
- Zoetemeijer, R., Cloetingh, S., Sassi, W. and Roure, F. (1993) Stratigraphic modelling of piggyback basins: record of tectonic evolution *Tectonophysics* **226**, 253–269
- Zonenshain, L. P., Kuzmin, M. I. and Napatov, L. M. (1990) *Geology of the USSR: a Plate Tectonic Synthesis*. *Am. Geophys. Union, Geodyn. Ser. No. 21*, 242 pp